To Reviewers:

This draft handbook builds from the Energy Facility Contractors Operating Group (EFCOG) Safety Analysis Working Group (SAWG) effort on a draft *Accident Analysis Guidebook* initially sponsored by Defense Programs in the early 2000s, and comments received on a 2013 draft of this *Accident Analysis Handbook*.

Please use the attached comment-resolution form to provide your comments and suggested solutions. Editorial comments are not necessary at this time, as this document will be reviewed by a Technical Editor. Suggestions for other technical topics may be considered for a future revision to this handbook.

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DOE HANDBOOK

HAZARD AND ACCIDENT ANALYSIS HANDBOOK

U.S. Department of Energy

Washington, D.C. 20585

FOREWORD

This U.S. Department of Energy (DOE) Handbook is approved for use by all DOE elements and their contractors.

10 Code of Federal Regulations (CFR) 830, *Nuclear Safety Management*, Subpart B, *Safety Basis Requirements*, establishes safety basis requirements for Hazard Category (HC) 1, 2, and 3 DOE nuclear facilities. This nuclear safety rule also identifies acceptable "safe harbor" methods for developing safety basis documents, such as DOE-STD-3009-94 Chg. Notice 1, *Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Facility Documented Safety Analysis*, or its successor document, DOE-STD-3009-2014, *Preparation of Nonreactor Nuclear Facility Documented Safety Analysis*. This Handbook provides additional details and examples supporting hazard and accident analysis, including applicable scientific theories, analysis techniques, practical examples, and lessons learned from DOE applications and experience. This Handbook is intended to help DOE contractors and personnel in preparing and reviewing documented safety analyses (DSAs). This Handbook is expected to serve as a resource and to facilitate more consistent safety analyses for DOE nuclear facilities, and cost-effective development of required safety analyses.

This Handbook addresses the following key topics: safety analysis process, analysis of major accident types (including fires, explosions, loss of confinement, chemical reactions, and natural phenomena events), nuclear criticality, source term analysis, radiological dispersion and consequence analysis, and chemical dispersion and consequence analysis.

DOE Order 252.1A, *Technical Standards Program*, dated 2-23-2011, states that DOE Handbooks provide "a compilation of good practices, lessons-learned, or reference information that serve as resources on specific topics." This Handbook does not contain requirements statements and cannot be made mandatory via DOE regulatory provisions or contracts. The application of the techniques described in this Handbook is not mandatory, and the methods and techniques may be used at the discretion of contractor line management.

Beneficial comments (recommendations, additions, deletions) and any pertinent data that may be of use in improving this document should be sent to:

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ACRONYMS

AED	Aerodynamic Equivalent Diameter
AEGL	Acute Exposure Guideline Level
ANS	American Nuclear Society
ANSI	American National Standards Institute
ARF	Airborne Release Fraction
BLEVE	Boiling Liquid Expanding Vapor Explosions
BPR	Burst Pressure Ratio
CFAST	Consolidated Model of Fire and Smoke Transport
CFD	Computerized Fluid Dynamics
CFR	Code of Federal Regulations
CLFL	Composite Lower Flammability Limit
DBA	Design Basis Accident
DDT	Deflagration to Detonation Transition
DOE	U.S. Department of Energy
DOE-STD	DOE Standard
DR	Damage Ratio
DSA	Documented Safety Analysis
EBA	Evaluation Basis Accident
EFCOG	Energy Facility Contractors Group
EPA	Environmental Protection Agency
ERPG	Emergency Response Planning Guideline
FDC	Flood Design Category
FMEA	Failure Modes and Effects Analysis
HA	Hazard Analysis
HC	Hazard Category
HAZOP	Hazard and Operational Analysis
HDBK	Handbook
HPR	Highly Protected Risk
HRR	Heat Release Rate
ILA	Immediate Landscaped Area
LFL	Lower Flammability Limit
LPF	Leakpath Factor
LPG	Liquified Petroleum Gas
MAR	Material at Risk
MOI	Maximally-Exposed Offsite Individual
NCD	NPH Design Category
NRC	Nuclear Regulatory Commission
PAC	Protective Action Criteria
PC	Performance Category
P&ID	Process and Instrumentation Drawing
PVB	Pressure Vessel Burst
RF	Respirable Fraction
RMP	Risk Management Program
SAC	Specific Administrative Control
SAWG	Safety Analysis Working Group
SIH	Standard Industrial Hazard
SIZ	Structure Ignition Zone

SME	Subject Matter Expert
SC	Safety Class
SDC	Seismic Design Category
SS	Safety Significant
SSC	Structures, Systems, and Components
STD	Standard
TED	Total Effective Dose
TEEL	Temporary Emergency Exposure Limit
TNT	Tri-Nitro-Toluene
TRU	Transuranic
TSR	Technical Safety Requirement
TWA	Time-weighted Average
UFL	Upper Flammability Limit
VCE	Vapor Cloud Explosion
VDC	Volcanic Design Category
WDC	Wind Design Category

Note: Definitions related to the DOE hazard and accident analysis process can be found in 10 CFR 830.3, DOE-STD-3009-2014, *Preparation of Nonreactor Nuclear Facility Documented Safety Analysis*, or the DOE Handbook DOE-HDBK-3010-94, *Airborne Release Fractions/Rates and Release Rates for Nonreactor Nuclear Facilities*. Other definitions related to accident phenomenology for evaluation of potential consequences such as physical and chemical effects are provided in the applicable references cited in the text.

1 INTRODUCTION AND OVERVIEW

This Handbook (HDBK) provides information intended to aid in the preparation of nuclear facility safety basis documentation and thereby support more consistent, documented safety analyses (DSAs) for the Department of Energy (DOE) nuclear facilities. The Handbook is a technical document containing methodology, data sources, and subject matter references relevant for performing and reviewing hazard, accident, and consequence analyses relevant to DOE nuclear facilities. The material may also be useful for courses at the National Training Center that are oriented towards the development of safety basis documents for DOE nuclear facilities.

This Handbook does not establish any new requirements, and is not to be treated as a requirement, for safety analyses of DOE nuclear facilities.

1.1 BACKGROUND

The Handbook makes use of drafts of an Energy Facility Contractors Group/Safety Analysis Working Group (EFCOG/SAWG) effort on an Accident Analysis Guidebook initially sponsored by the DOE Defense Programs in the early 2000s. This material has been updated and augmented to include topics that result from developments since that earlier effort (including insights from development of DOE Standard (STD) 3009-2014, *Preparation of Nonreactor Nuclear Facility Documented Safety Analysis)* as well as examples of application. When used without a 2-digit or 4-digit year number after "DOE-STD-3009," it refers to both the 1994 and 2014 versions of the DOE Standard. Otherwise, specific versions are referenced. This Handbook will be revised periodically as beneficial comments (recommendations, additions, deletions, etc.) and any pertinent data that may be of use in improving this document are provided as discussed in the Foreword.

1.2 APPLICABILITY AND RELATIONSHIP TO SAFETY BASIS DIRECTIVES

This Handbook is applicable to development of DSAs for DOE nonreactor nuclear facilities. 10 Code of Federal Regulations (CFR) 830, *Nuclear Safety Management*, Subpart B, Safety Basis Requirements, establishes safety basis requirements for Hazard Category (HC) -1, 2, and 3 DOE nuclear facilities. This nuclear safety rule also identifies acceptable "safe harbor" methods for developing safety basis documents, such as DOE-STD-3009-1994 Chg. Notice 1, *Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Facility Safety Analysis Reports*, or its successor document, such as DOE-STD-3009-1994 Chg. Notice 3, *Preparation Guide for U.S. Department of Energy Nonreactor Nuclear Facility Documented Safety Analysis*, or DOE-STD-3009-2014. The information in this Handbook is also relevant to the other acceptable methods for development of safety basis document, e.g., a basis for interim operations (STD and Title) or a DSA for environmental restoration (STD and Title), as they all involve hazard identification and analysis, identification of hazard controls, safety classification of these hazard controls, and derivation of technical safety requirements (TSRs) for safe operation of a nonreactor nuclear facility. Safety analysis is a documented process to:

- Provide systematic identification of hazards within a given DOE operation;
- Analyze and evaluate potential accidents and their associated risks; and
- Describe and analyze the adequacy of the measures taken to eliminate, control, or mitigate identified hazards.

1.3 SCOPE AND OUTLINE

All of the safe harbor standards identified above include a safety analysis process that consists of the following major steps:

- Hazard Analysis (HA) (including hazard identification and evaluation);
- Accident Analysis (including accident definition and consequence analysis); and
- Control Selection.

The recently revised DOE-STD-3009-2014 was restructured and now provides criteria and guidance organized in this manner. Further, it includes lessons learned from use of DOE-STD-3009-94. Therefore, this Handbook utilizes excerpts from DOE-STD-3009-2014 as the starting point for the amplifying guidance and good practices. This guidance and good practices can be utilized to support development and maintenance of DSAs of any of the nonreactor safety harbors. This Handbook is organized as follows:

- Chapter 2, *Hazard Analysis Process*, addresses hazard identification and evaluation, including hazard evaluation methods and safety control identification.
- Chapter 3, *Accident Type Selection and Analysis Overview*, provides a high level overview of the events that were identified in the hazard evaluation table are evaluated for further accident analysis, provides an overview of the accident analysis process, and discusses two key topics; (1) assumption and initial conditions and (2) conservatism in analysis.
- Chapter 4, *Evaluation of Impacts from Major Accident Types*, addresses the analysis of accident scenarios. The various topics covered provide information for evaluating the magnitude of the accidents and the accident environments that result so that the amount of radioactive or hazardous material affected is defined. This information is necessary in order to determine the source term available for release from the facility and to evaluate the capability of safety structures, systems, and components (SSCs) to survive the accident environments and provide their safety functions when called upon.
- Chapter 5, *Source Term Analysis*, addresses development of the amount of radioactive or hazardous material released from a given confinement volume under the stress posed by a hypothetical accident. Source term estimations include quantifying material at risk, damage ratio, airborne release fractions (ARFs) /rates and respirable fractions (RFs), and leakpath factor.
- Chapter 6, *Atmospheric Dispersion and Radiological Consequence Analysis*, addresses environmental (air, water) transport and diffusion, and the models available for radiological releases. This chapter discusses the different types of radiation and the effects they can have on the human body, its organs, and its tissues.
- Chapter 7, *Chemical Dispersion and Consequence Analysis*, addresses the same areas as Chapter 6, but is oriented towards chemical releases. Where the models and explanations are the same as for radiological releases, Chapter 7 refers to the appropriate sections of Chapter 6.
- Chapter 8, Hazard *Control Selection and Classification*, addresses selection of safety significant (SS) and safety class (SC) controls that are credited in the hazard evaluation or accident analysis.
- Appendices include more technical details as referenced in the chapters or provide additional background information.

2 HAZARD ANALYSIS (HA) PROCESS

This chapter addresses HA techniques for the identification and evaluation of hazards, and the identification of safety controls to prevent or mitigate accidents.

2.1 OVERVIEW

A DSA HA as defined by DOE-STD-3009 consists of: (a) hazard identification and characterization, (b) hazard categorization, and (c) hazard evaluation which includes identification and safety classification of controls to prevent or mitigate potential hazard or accident scenarios. This chapter also discusses the documentation of the HA. This Handbook does not discuss hazard categorization.[1]

A document that may be useful in developing an HA for DSA development is DOE-HDBK-1163-2003, *Integration of Multiple Hazard analysis Requiremets and Activities*. This Handbook captures the insights from a joint DOE/EFCOG Chemical Safety Topical Committee task in 2001 that evaluated possible methods for integrating HA activities with potential overlap such as radiological, chemical, emergency preparedness, environmental and others. This effort identified and reviewed HA requirements and issues, collected numerous sources of good practices information, and evaluated possible methods for integrating HA activities. The Handbook provides an overview of current DOE directives and federal regulations, highlights opportunities for integrating HA activities, and provides approaches that can improve effectiveness of HA while improving cost performance. The Handbook identifies numerous requirements having direct reference to hazard identification, HA, hazard evaluation, hazard assessment, accident analysis, and risk analysis or risk assessment. A comparison of the purpose and expectations of HA requirements is summarized in its Appendix A. Each requirement source has a different focus such as emergency management, nuclear safety, chemical safety, or worker protection. However, common objectives are found among certain groups of requirements that can be characterized as addressing either (1) facility-level safety, (2) task-level safety, or (3) protection against a specific hazard or hazardous condition (e.g., beryllium, fire, criticality, natural phenomena).

2.2 HAZARD IDENTIFICATION AND CHARACTERIZATION

The objective of hazard identification for the DSA is to systematically and comprehensively identify the natural and man-made hazards, with respect to form, type, location, and quantity, associated with the facility. It is then used in the hazard evaluation process to postulate hazard scenarios and evaluate the need for preventive and mitigative controls.

For DSAs prepared in accordance with 10 CFR 830, Subpart B, the key to successful hazard identification is that it ensures comprehensive identification of the hazards associated with the full scope of facility processes, associated operations, such as handling of fissionable materials and hazardous waste, and work activities covered by the DSA. Hazard identification does not yield specific hazard scenarios to analyze. Rather, it yields initial data from which hazard scenarios are subsequently defined in hazard evaluation. Obviously, the overall quality of hazard scenario definition will be in direct proportion to the quality of the initial data gathered.

[1] Guidance for performing hazard categorizations is provided in DOE-STD-1027-92, Chg. Notice 1, *Hazard Categorization and Accident Analysis Techniques for Compliance with DOE Order 5480.23, Nuclear Safety Analysis Reports.*

Hazard identification is the process of characterizing radiological and hazardous materials and energy sources, in terms of quantity, form, and location. Commercial industry practices for hazard identification, such as those described in CCPS (2008), provide guidance for a comprehensive identification of hazards.

The hazard identification process involves:

- Data gathering;
- Summarizing results in tables; and
- Screening standard industrial hazards (SIHs) (common industrial hazards can cause uncontrolled release of materials of concern, i.e. radioactive or hazardous materials).

2.2.1 DATA GATHERING

Hazard identification efforts begin with an information review of existing documentation, such as:

- Facility and process descriptions (including available drawings and flow sheets);
- Historical radiological and hazardous chemical inventory records;
- Existing safety documentation (e.g., material safety data sheets, health and safety plans, DOE Integrated Safety Management System activity or job hazards analyses, criticality safety evaluation reports, fire hazards analyses, emergency planning hazards assessments, previous safety analyses);
- Operating and support procedures;
- Previous occurrence reports for the facility and from general industry that may be of interest; and
- Design media for existing facilities or being developed for new facilities.

As these are performed, the raw data is collected in a checklist (as discussed in Section 2.2.2 below).

Comprehensive identification of hazards is most effectively accomplished by a team comprised of safety analysts, system/process engineers, operational and support staff, and other Subject Matter Experts (SMEs) as needed.

Once documented sources have been reviewed, a physical walk-down of the facility occurs to aid in comprehensive identification of hazards and their potential interactions. Such walk-downs are typically conducted with a floor plan upon which the most significant details are noted (e.g., specific gloveboxes by operation, major inventories and energy sources, significant system interconnections, critical piping routes). Other details can be recorded in checklists and notebooks for completeness. If the facility is being designed, the floor plan can still be conceptually walked down using process and instrumentation drawings (P&IDs) at whatever stage of development is available. It is important to note, however, that if P&IDs are based on evolving design of a new facility, the hazard identification will need to be re-verified against the final design and as-built construction during the development of the DSA to support authorizing operations.

2.2.2 CHECKLISTS/DATA RECORDING

Checklists are used to ensure the hazard identification process is comprehensive and thorough. These lists provide a generic listing of hazards to look for in terms of radioactive and hazardous material types, energy sources, moving components, potential falling objects, etc. Hazard identification preparers use such checklists to systematically identify the presence or absence of hazards for a given area, from individual gloveboxes or operations to entire rooms. The degree to which an individual checklist is extended to entire rooms or even the whole facility, as opposed to multiple operation-specific checklists, is normally a function of complexity. Less complex operations or activities support broader use of individual checklists.

The raw data of hazard identification can be recorded in a variety of ways. The critical information to be specifically noted in any recording mechanism is the hazard itself, its type, magnitude and location, and sufficient descriptive notes to allow the hazards analysis team to place individual hazards in appropriate context.

Materials of concern for release (or potential hazards in direct contact with material of concern) are identified separately. Bounding inventory values of radiological or hazardous materials are needed for the hazard evaluation and accident analysis, consistent with the maximum quantities of material that are stored and used in facility processes. It should be based on the design and operational intent with some added margin for conservatism to provide for operational flexibility. Inventory data may be obtained from flowsheets, vessel sizes, contamination analyses, maximum historical inventories, and similar sources. That is important since the definition of materials of concern must ultimately support the conclusion that a given set of analytical assumptions are appropriately conservative. This level of conservatism need not be based on what can be physically put into an area such as assuming all vessels and gloveboxes are at their maximum allowed criticality safety limits which could result in orders of magnitude more Material at Risk (MAR) that could ever be in the facility and mischaracterizes the hazard and thus the associated risk of facility operations. However, a special case is for HC-3 facilities to stay below the HC threshold sum-of-fractions with an appropriate operating margin.

An example of a checklist for a DOE nuclear facility is shown in Table 2-1. Other checklists to identify hazards and energy sources have been developed in the DOE Complex and reflect site-specific and facility-specific hazards. Regardless of what checklist and summary table (as discussed in Section 2.2.3) is used, the hazard analyst should work one-on-one with an individual SME and operations representative(s) to fill-out those parts related to the SME's area of expertise, and include facility walk-downs. The hazard analyst should then compile a complete draft of the table and present it to the HA team for review. This is a much more efficient way to complete the exercise than to have the entire HA team sit in a conference room discussing each and every item.

Table 2-1. Hazard Identification Checklist Example.
(Identify facility, location or process, etc.)

No.	Item	Hazard present (Y/N)	Description (quantity, form, location)	Disposition (SIH, accident initiator /contributor)
1.0	**Electrical**			
1.1	Battery banks	Y		
1.2	Cable runs			
1.3	Diesel generators			
1.4	Electrical equipment			
1.5	Heaters			
1.6	High voltage (> 600V)			

No.	Item	Hazard present (Y/N)	Description (quantity, form, location)	Disposition (SIH, accident initiator /contributor)
1.7	Locomotive, electrical			
1.8	Motors			
1.9	Power tools			
1.10	Pumps			
1.11	Service outlets, fittings			
1.12	Switchgear			
1.13	Transformers			
1.14	Transmission lines			
1.15	Wiring/underground wiring			
1.16	Other			
2.0	**Thermal**			
2.1	Boilers			
2.2	Bunsen burner/hot plates			
2.3	Electrical equipment			
2.4	Electrical wiring			
2.5	Engine exhaust			
2.6	Furnaces			
2.7	Heaters			
2.8	Lasers			
2.9	Steam lines			
2.10	Welding surfaces			
2.11	Welding torches			
2.12	Other			
3.0	**Pyrophoric Material**			
3.1	Pu and U metal			
3.2	Other			
4.0	**Spontaneous Combustion**			
4.1	Cleaning/decon solvents			
4.2	Fuels (gasoline, diesel fuel, etc.)			
4.3	Grease			
4.4	Nitric acid and organics			
4.5	Paint solvents			
4.6	Other			
5.0	**Open Flame**			
5.1	Bunsen burners			
5.2	Welding/cutting torches			
5.3	Other			
6.0	**Flammables**			
6.1	Cleaning/decon solvents			
6.2	Flammable gases			
6.3	Flammable liquids			
6.4	Gasoline			
6.5	Natural Gas			
6.6	Paint/paint solvent			
6.7	Propane			
6.8	Spray paint			
6.9	Other			
7.0	**Combustibles**			
7.1	Paper/wood products			
7.2	Petroleum based products			
7.3	Plastics			

No.	Item	Hazard present (Y/N)	Description (quantity, form, location)	Disposition (SIH, accident initiator /contributor)
7.4	Other			
8.0	**Chemical Reactions**			
8.1	Concentration			
8.2	Disassociation			
8.3	Exothermic			
8.4	Incompatible chemical mixing			
8.5	Uncontrolled chemical reactions			
9.0	**Explosive Material**			
9.1	Caps			
9.2	Dusts			
9.3	Dynamite			
9.4	Electric squibs			
9.5	Explosive chemicals			
9.6	Explosive gases			
9.7	Hydrogen			
9.8	Hydrogen (batteries)			
9.9	Nitrates			
9.10	Peroxides			
9.11	Primer cord			
9.12	Propane			
9.13	Other			
10.0	**Kinetic (Linear and Rotational)**			
10.1	Acceleration/deceleration			
10.2	Bearings			
10.3	Belts			
10.4	Carts/dollies			
10.5	Centrifuges			
10.6	Crane loads (in motion)			
10.7	Drills			
10.8	Fans			
10.9	Firearm discharge			
10.10	Fork lifts			
10.11	Gears			
10.12	Grinders			
10.13	Motors			
10.14	Power tools			
10.15	Presses/shears			
10.16	Rail cars			
10.17	Saws			
10.18	Vehicles			
10.19	Vibration			
10.20	Other			
11.0	**Potential (Pressure)**			
11.1	Autoclaves			
11.2	Boilers			
11.3	Coiled springs			
11.4	Furnaces			
11.5	Gas bottles			
11.6	Gas receivers			
11.7	Pressure vessels			
11.8	Pressurized system (e.g., air)			

No.	Item	Hazard present (Y/N)	Description (quantity, form, location)	Disposition (SIH, accident initiator /contributor)
11.9	Steam headers and lines			
11.10	Stressed members			
11.11	Other			
12.0	**Potential (Height/Mass)**			
12.1	Cranes/hoists			
12.2	Elevated doors			
12.3	Elevated work surfaces			
12.4	Elevators			
12.5	Lifts			
12.6	Loading docks			
12.7	Mezzanines			
12.8	Floor pits			
12.9	Scaffolds and ladders			
12.10	Stacked material			
12.11	Stairs			
12.12	Other			
13.0	**Internal Flooding Sources**			
13.1	Domestic water			
13.2	Fire suppression piping			
13.3	Process water			
13.4	Other			
14.0	**Physical**			
14.1	Sharp edges or points			
14.2	Pinch points			
14.3	Confined space			
14.4	Tripping			
15.0	**Radiological Material**			
15.1	Radiological material			
16.0	**Hazardous Material**			
16.1	Asphyxiants			
16.2	Bacteria/viruses			
16.3	Beryllium and compounds			
16.4	Biologicals			
16.5	Carcinogens			
16.6	Chlorine and compounds			
16.7	Corrosives			
16.8	Decontamination solutions			
16.9	Dusts and particles			
16.10	Fluorides			
16.11	Hydrides			
16.12	Lead			
16.13	Oxidizers			
16.14	Poisons (herbicides, insecticides)			
16.15	Other			
17.0	**Ionizing Radiation Sources**			
17.1	Contamination			
17.2	Electron beams			
17.3	Radioactive material			
17.4	Radioactive sources			
17.5	Radiography equipment			
17.6	X-ray machines			

No.	Item	Hazard present (Y/N)	Description (quantity, form, location)	Disposition (SIH, accident initiator /contributor)
17.7	Other			
18.0	**Non-ionizing Radiation**			
18.1	Lasers			
18.2	Other			
19.0	**Criticality**			
19.1	Fissile material			
20.0	**Non-facility Events**			
20.1	Aircraft crash			
20.2	Explosion			
20.3	Fire			
20.4	Power outage			
20.5	Transportation accident			
20.6	Other			
21.0	**Vehicles in Motion**			
21.1	Airplane			
21.2	Crane/hoist			
21.3	Forklifts			
21.4	Heavy construction equipment			
21.5	Helicopter			
21.6	Train			
21.7	Truck/car			
22.0	**Natural Phenomena**			
22.1	Earthquake			
22.2	Flood			
22.3	Lightning			
22.4	Rain/hail			
22.5	Snow/freezing weather			
22.6	Straight wind			
22.7	Tornado			

Additional information is provided in CCPS (2008), and many DOE sites have developed their site-specific checklist for DSA hazard identifications.

2.2.3 HAZARD SUMMARY TABLE DEVELOPMENT

The checklists are used to develop a summary table to ensure that the range of information developed during the course of performing the hazard identification is appropriately documented for presentation in the DSA or its supporting reference to a hazard identification report or HA report that includes both hazard identification and hazard evaluations. The range of information captured in the hazard identification table is designed to ensure that the minimum hazard identification results are established, appropriate screening of hazards is performed, and information needed to perform an effective and efficient hazards evaluation is established.

The raw material from the hazard identification checklists can quickly become unmanageable for presentation in the DSA, which isn't generally included in the DSA. The data have to be analyzed, groupd, and organized into a useful summary form. This will help facilitate consistent presentation of the hazards, their magnitude, and location for later use in developing the hazard evaluation or accident analysis.

Table 2-2 is an example a Hazard Summary Table form for a simple facility that can be developed to integrate the results of the Table 2-1 checklists that may be developed for specific areas or processes within the facility. Other hazard summary tables have been developed in the DOE Complex and reflect site-specific and facility-specific hazards. Some sites do not include the screening of SIHs on the summary table, and instead document the screening in the DSA results section of the hazard identification effort. Either approach is suitable as long as there is clear documentation of hazards that are screened out from further evaluation in the hazard evaluation (note that many SIHs are evaluated in the hazard evaluation as an initiator or contributor to a radiological or other hazardous material release, which needs to be acknowledged somewhere in the hazard identification results section). For more complicated or large facilities, including all of the broad groupings of hazards in one table may result in too much information for the DSA Chapter 3, and breaking out the table by hazard types, or by type of operations, or both, may be a more effective method to summarize the hazards, quantities, form, and location. Some sites have issued separate hazard identification reports to capture the checklists with multiple summary tables, and these are referenced in the DSA along with including a high level summary of results.

Table 2-2. Building XXX Hazard Identification Summary Table.

Hazard Type	Location	Form	Quantity	Remarks / Screening	References
Radioactive materials	(room, area, etc.)	(gas, liquid, powder, metal, fines, etc.)	(Curies or mass by form)	(Identify whether this is SIH and can be screened from the hazard evaluation.)	(Cite supporting reference, or applicable SMP, or industry code/standard if screened out.)
Direct radiation exposure					
Nuclear criticality					
Chemicals (corrosives, toxics, reactions)					
Flammable/ combustible materials					
Explosive material					
Electrical energy					
Kinetic and potential energy					
Pressure-volume					
Thermal energy					
Natural phenomena					
Other					

These compilation of information reviews and facility walk-downs constitute initial information. Iterations between the hazard identification and hazard evaluation phases are likely necessary in order to ensure completeness. This table can also identify hazards that were screened out as discussed in the next section (Section 2.2.4).

2.2.4 STANDARD INDUSTRIAL HAZARD SCREENING

An extensive listing of operation-specific hazards can be provided in Tables 2-1 and Table 2-2. Then, DSAs screen selected hazards for further hazard evaluation to generate a safety control set to prevent or mitigate hazard scenarios or hazardous conditions.

Although the hazard identification process is comprehensive of all radiological and non-radiological hazards, DSAs are not intended to analyze and provide controls for SIHs such as burns from hot objects, electrocution, and falling objects. These hazards are adequately analyzed and controlled in accordance with 10 CFR Part 851, *Worker Safety and Health Program*, and are analyzed in a DSA only if they can be an accident initiator, a contributor to a significant uncontrolled release of radioactive or other hazardous material (for example, 115-volt wiring as initiator of a fire), or considered a unique worker hazard such as explosive energy. Most recent guidance on SIH and chemical screening is provided in DOE-STD-3009-2014, Appendix A, Sections A.1 and A.2, respectively, or those methods that have been accepted in existing approved DSAs being updated. Some hazards may be summarized from the checklists by group of operations or locations, e.g., for welding and grinding operations that present a “thermal” hazard” in multiple areas. The basis for any identified hazard or class of hazards excluded from further DSA hazard evaluation is documented. This can be accomplished by including a reference to a code or standard or short justification statement on the hazard evaluation table, or for more complicated justifications, in the DSA hazard identification results section. This is not intended to be a lengthy exercise but provide sufficient detail for reviewers to confirm the adequacy of screening out the hazard from further hazard evaluation.

Note again, however, that exclusion as an SIH precludes only individual analysis of a hazard and associated safety SSC/specific administrative control (SAC) control designation. Such hazards are still considered for their possible impact on radiological or other chemical accident initiation or progression, or their ability to impact the safe operation of the facility (e.g., inability to perform a SAC).

2.3 HAZARD EVALUATION

Hazard evaluation is defined in CCPS (2008) as:

> *“The analysis of the significance of hazardous situations associated with a process or activity. Uses qualitative techniques to pinpoint weaknesses in the design and operation of facilities that could lead to accidents.”*

As noted in that definition, the primary purpose of hazard evaluation is to improve design and operations, although the need for improvements is qualitatively evaluated in accordance with subjective criteria on a case-by-case basis. Use of a systematic process for evaluation, however, joins hazards with initiators and consequences, called a hazard scenario, in a manner useful for multiple purposes.

A DSA hazard evaluation is defined in DOE-STD-3009 more simply as assessment of hazardous situations associated with a process or activity. The DSA hazard evaluation provides: (a) an assessment of the facility hazards associated with the full scope of planned operations covered by the DSA, and (b) the identification of controls that can prevent or mitigate these hazards or hazardous conditions. It analyzes normal operations (e.g., startup, facility activities, shutdown, and testing and maintenance

configurations) as well as abnormal[2] and accident conditions. In addition to the process-related hazards identified during the hazard identification process, the hazard evaluation also addresses natural phenomena and man-made external events that can affect the facility.

The term HA is used in a generic sense to indicate the hazard identification and evaluation process, as hazard identification is frequently completed with the hazard evaluation. Consideration is given to the potential for accidents associated with facility activities, external events, or natural phenomena. Hazards evaluation is the primary focal point of the facility HA and the starting point for the accident analysis and control set selection. Through the HA process, the hazards and a comprehensive set of postulated hazard scenarios (hazardous conditions or situations) associated with the facility activities are systematically and qualitatively or semi-quantitatively evaluated, using one or more of the hazard evaluation techniques described in Section 2.4, Hazard Evaluation Methods.

The hazard evaluation study begins by:

- Defining the scope of the HA. The scope of an HA can vary from a single process in a single room to an entire facility with multiple processes, and needs to consider the full scope of operations and activities as included in the Section 2.2 hazard identification. The scope of activities to be evaluated by the analysis includes any activities that can occur when significant quantities of hazardous materials are present. These include DSA-authorized processes and experiments in the facility, off-shift activities, and any hazard associated with maintenance and support activities that can occur when significant quantities of hazardous materials are present. Importantly, physical boundaries, process/support system interfaces, and interfaces with other facilities need to be defined in the HA scope. These boundaries/interfaces need to be evaluated to determine if/when hazards cross the boundaries/interfaces; and what, if any controls, might be required.
- Evaluating hazards associated with authorized activities, external events, or natural phenomena as discussed in Section 2.2.1 to develop a comprehensive list of postulated hazard or accident scenarios.
- Evaluating hazardous materials and energy sources to determine possible interactions that could lead to accident conditions.
- Evaluating factors such as hardware, process materials, and mission activities that could affect the initiation and progression of the accident conditions.
- Reviewing applicable safety documentation, process history, occurrence reports, and other information sources to evaluate hazardous conditions or potential accidents associated with the facility.

[2] An abnormal event is any deviation from the design or operational intent. For example, if the design and operational intent is to perform a transfer at 70 ± 5gpm, then a flow rate less than 65 gpm or greater than 75 gpm is an abnormal event. An abnormal event can result in undesirable consequences, which can be categorized as either an operational upset (e.g., delay in processing) or a specific hazardous condition (e.g., uncontrolled release of a hazardous material). Accidents occur when abnormal events that can result in a hazardous condition are not prevent or controlled. See DOE-STD-3009-2014 for further discussions of abnormal situations, including Section A.9, Defense-in-Depth.

All activities within the facility boundaries are considered in the analysis. The HA team must define where these boundaries start and stop. Considerations for the HA team include:

- Do activities start at the door of the facility, at the loading dock, or at an outside staging or storage area?
- If two facilities share common space, at what point does one facility analysis start and the other stop?
- Do immediately adjacent facilities pose hazards to the facility (e.g., do they contain toxic materials that could disable the operator, or contain flammable gas that could penetrate fire barriers and initiate an event in the facility of concern)?
- Can the facility be segmented to reduce the MAR for accident consideration in accordance with DOE-STD-1027-92, Chg. Notice 1?

A particularly challenging interface involves transportation activities. For transportation analyses, the scope of the analysis generally begins when there is a custody transfer and ends when custody is transferred back. Each nuclear facility takes ownership of material or experiments (i.e., it is in scope), once the material is removed from the truck and a transfer of custody occurs. Staging activities on a loading dock or other location exterior to the facility are within the scope of the facility analysis, unless it is specifically evaluated in the transportation safety document or DSA.

Following this study, the hazards evaluation process is completed with the documentation of hazardous conditions (hazard scenarios) identified, followed by the estimation of the associated frequencies and consequences based on potential interactions between hazardous materials and energy sources and not considering the effect of crediting preventive and mitigated controls (i.e., unmitigated analysis). Table 2-3 provides a suggested correlation of the hazardous energy sources to typical accident types or categories. A similar correlation is provided in Table 3.2-1, “Hazard Sources and Potential Events,” in DOE-STD-5506-2007, *Preparation of Safety Basis Documents for Transuranic (TRU) Waste Facilities*.

Table 2-3. Correlation of Hazardous Energy and Material Sources to Accident Types/Categories.

Accident Category*	Hazard Energy and Material Source Groups	
E-1: Fire	Electrical Thermal Friction Pyrophoric Material Spontaneous Combustion	Open Flame Flammables Combustibles Chemical Reaction
E-2: Explosion	Potential (Pressure) Explosive Materials Chemical Reactions	
E-3: Loss of Containment or Confinement	Radioactive material Hazardous Material	
E-4: Direct Radiological Exposure	Ionizing Radiation Sources	
E-5: Nuclear Criticality	Fissile Material	
E-6: External Hazards	Non-Facility Events (e.g., aircraft crashes) Vehicles in Motion Cranes	
E-7: Natural Phenomena	Natural Phenomena- Seismic Event, Wind, Flood, etc.	

*The E-number assigned to the accident categories is for ease of data management, and any numbering scheme could be used if deemed necessary.

A graded approach as defined in 10 CFR 830.3 and DOE-STD-3009 is applied to the selection of hazard evaluation technique(s) and developing the hazard evaluations. The selection is based on several factors including the complexity and size of the operation being analyzed, the type of operation, and the inherent nature of hazards being evaluated. Additional guidance for selecting a hazard evaluation technique is presented in CCPS (2008).

2.4 HAZARD EVALUATION METHODS

Chapter Four of *Guidelines for Hazard Evaluation Procedures* (CCPS, 2008) provides a summary listing of the major methodologies utilized in hazard evaluation. The discussions are oriented toward the chemical industry, but the basic strengths and weaknesses of each method are consistent across applications. Examples of five of the 12 major methods discussed are provided in this chapter. These examples are most suitable for DSA hazard evaluations to evaluate select processes from the example facilities in DOE-HDBK-3010-94, *Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities*.

It is important to note that none of these industry hazard evaluation methods were designed to generate a DSA hazard evaluation and do not yield hazard scenarios, nor were they designed to identify SS and SC SSCs or SACs. Those results are uniquely defined for DOE usage to develop a DSA. Thus, one does not normally see the raw information generated from the industry hazard evaluation in a DSA, however, it is a necessary step to developing hazard scenarios. The hazard evaluation is performed to understand facility vulnerabilities and potential hazard scenarios. Those insights are then distilled into a DSA hazard evaluation table and are used for safety classification of controls and derivation of TSRs.

The common methodologies utilized vary in both complexity and focus. The more specific the focus (e.g., process interactions, specific subcomponent failures) of a given methodology is, the less amendable the product generated is to direct incorporation in the DSA. That is because the methodology tends to generate a level of detail that can needlessly complicate or confuse the DSA presentation. Depending on the scope of the HA, multiple HA methodologies may be used. For example, the Hazard and Operational Analysis (HAZOP) methodology is perfect for analyzing a chemical process within a facility, but the What-If methodology is better suited for evaluating NPH and external events with the potential to affect the entire facility.

The simplest method for hazard evaluation is a checklist. It is a list of specific items that identify already known or understood hazards (e.g., fires, explosions, spills) and can be augmented with design information. In DOE applications, however, it has been observed that the use of a checklist for both hazard identification and hazard evaluation tends to produce rote results in the DSA hazard evaluation that can be devoid of operational-specific insight. It is preferable that, if checklists are utilized for the DSA hazard evaluation, they are used in conjunction with the "what if" methodology.

Although not a specific hazard evaluation technique, a document that may be useful in developing a hazard evaluation for DSA development is the *Hazard and Barrier Analysis Guide* (DOE-EH-33). In 1996, the DOE Environment & Health Office of Operating Experience Analysis and Feedback sponsored the development of simplified analytical techniques and tools for the analysis of operating events at DOE facilities to promote its theme of safety management through analysis. The Guide was meant to provide to the DOE complex a set of simple and straightforward tools to devise effective strategies for preventing accidents, and to evaluate accidents and accident precursors which have occurred across the DOE complex. The Guide was developed to achieve the following results: (1) identification of hazards that are associated with a specific activity, (2) identification, evaluation and implementation of a set of effective barriers that protects workers from these hazards, and (3) estimation of barrier failure likelihoods to arrive at an estimate of the risk of injury, fatality, environmental release, or property damage. Barriers may be physical barriers, procedural or administrative barriers, or human action. To aid in the process of barrier identification, a Hazard-Barrier Matrix was developed. The Hazard-Barrier Matrix was constructed by considering hazards that are typically associated with work at DOE facilities, and identifying the barriers that are likely to provide protection against these hazards. The Guide considered the reliability of a barrier in terms of its expected failure probabilities or rates. Where facility specific databases do not exist, generic failure data can be utilized to estimate the reliability of systems and components, an approach taken by the commercial nuclear industry before plant specific databases were developed. This was the approach adopted in the Guide for estimating both system as well as human reliability. A set of recommended generic system, component and human failure rates appropriate to DOE operations, together with guidance on utilizing them, was incorporated in the Guide. It should be recognized that this Guide will require supplementary analysis and information to meet all the expectaions for a hazard evaluation for development of a DSA as described in DOE-STD-3009.

2.4.1 WHAT IF METHODOLOGY

The "what if" methodology is a loosely structured, brainstorming technique. Analysts utilizing this method formulate a series of questions, each beginning with the phrase "What if…" An example might be "What if the liquid tank overflows?" The hazard evaluation would discuss ways in which the tank might overflow (e.g., initiators and overall event progression sequences), the consequences of overflow, and what preventive and mitigative control responses are available. The extent of the discussion inherently grades based on consequence. If the liquid in question is simply water with trace contamination, the discussion will reach resolution much quicker than if the liquid is a highly volatile, toxic substance.

To provide proper structure for comprehensive results, the examination progresses in an organized manner, typically from the beginning of the activity/operation to the end. Well-designed checklists can provide additional structure that limits the potential for events to be missed. Further, while a variety of potential outcomes can be identified, it is important to identify the ultimate consequence that is physically plausible. Analysts should not stop with the assumption that a given control functions. To do so can result in failure to identify vulnerabilities, and is also inconsistent with DOE's stated intent for unmitigated analyses.

The strengths of the "what if" methodology include broad applicability, ease of use, and its adherence to natural thought processes. Weaknesses include a greater potential for neglecting interaction issues and for missing some events altogether. The quality of "what if" results can vary significantly based on the experience of the individual leading that effort. Generally, "what if" analysis is most suited to simple operations and activities where the potential end states of each step are discrete and easy to identify. Manual operations/activities are often ideal for "what if" analysis.

The TRU Waste Facility defined in Appendix B of DOE-HDBK-3010-94 is an ideal example of an operation amenable to a "what if" analysis. So is the plutonium Production Support Lab also defined in DOE-HDBK-3010-94 Appendix B. The common feature of both is that they do not constitute material/chemical processes at all, let alone complex processes. They consist of discrete, manual operations whose interaction boundaries are well defined.

Consider the liquid sampling glovebox in the Production Support Lab. It is a manual operation that handles 20 ml sample vials. A simple walk-down of the process generates obvious "what-if" questions as shown on Table 2-4.

Table 2-4. "What-If" Hazard Analysis Example.

"What if…"	**Possible Answers**
1. …a collection of vials is dropped while being entered into the glovebox?	1. Broken vial(s), small Pu airborne release, minor worker exposure.
2. …the sample recycle bottle is dropped while coming out of the glovebox?	2. Spill, small Pu airborne release, minor worker exposure.
3. …liquid is spilled within the glovebox?	3. See #1 and #2 above, without direct worker exposure potential.
4. …the sample recycle bottle is overfilled (i.e., double batch of high concentration of fissile solution)?	4.a. Criticality Safety Evaluation shows large margin = no issue or 4.b. Criticality Safety Evaluation shows limited margin = potential criticality
5. …the glovebox inventory of hexone solvent ignites?	5.a. Potential glovebox confinement breach and/or 5.b. airborne Pu release (larger release potential than spill)
6. …more samples are brought into the glovebox than its allowable storage spaces?	6. No specific consequence (potential deviation in operational practice that should be evaluated).
7. …planchette(s) are dropped outside of glovebox	7. No significant consequence (quantities of material are too small)

The above list is not exhaustive, but demonstrates the basic idea. This questioning process would be repeated for each of the specific operations and general activities authorized in the facility. The resulting complete set of questions and answers would then be sifted through, combined and amplified as necessary to generate specific hazard scenarios in the DSA hazard evaluation table. For example, if the potential exposure consequences are sufficiently limited, all liquid spills might be combined into one representative hazard scenario that credits no SSCs. Or if only one or two of the liquid spill scenarios could pose significant exposure potential, those would be documented as individual events alongside the low consequence representative scenario.

It is important to not inappropriately combine scenarios. In the hypothetical case presented in the previous paragraph, suppose one distinct spill with significant consequences is rolled up with all other spills. The hazard evaluation would then identify any credited controls for one scenario as applying to all glovebox liquid handling operations. Likewise, fires and spills should not be combined into one event. They are separate events with separate initiators and potential control sets. The required clarity in analysis and in evaluation of the most important preventive and mitigative controls is lost if these disparate elements are jumbled together.

As a final note, it is reiterated that the "what if" technique is not restricted to low consequence operations. Consider the case of the Plutonium Recovery Facility defined in Appendix B of DOE-HDBK-3010-94. The front end Feed Preparation Operation can contain kilograms of plutonium. It is nonetheless a set of discrete, manual operations for which the "what if" technique is suitable. The same could be said for the Oxide Dissolution Line (DOE-HDBK-3010-94 Figure B.6) which, while a chemical process, is a batch process run in sequential steps. The "what if" technique is suitable for any application where the analysts do not find complexity and potential interactions difficult to address.

2.4.2 HAZARD AND OPERATIONAL ANALYSIS (HAZOP)

A different type of methodology specifically designed to investigate chemical process performance is a HAZOP. This method requires a significantly greater investment of time and resources than a "what if" analysis. It is a highly formal, systematic method for prompting team members to identify and assess the significance of system malfunctions or improper operations at each step of a process.

The HAZOP method divides a process into discrete sections, with the intent of each section defined. The method then examines deviations from intent by combining parameters with guide words. Examples of parameters include flow, pressure, temperature, composition and even more conceptual items such as containment. Examples of guide words include "no, more, less, high, low, as well as, partial, reverse, wrong type, sooner than, later than, breach, etc." The HAZOP team might start examining a section by postulating "no flow." They would then identify the causes of no flow, the consequences of no flow, and what preventive and mitigative controls are available or may be recommended for consideration, or other action items that may require further investigation. The team subsequently proceeds to "low flow," followed by "high flow" and so on. Note also that when significant consequence potential is identified, it is important to trace causality back to previous sections examined if the deviation of interest originates there. This develops understanding of integrated process behavior, as opposed to simply focusing on discrete behavior of isolated components.

It should be clear from this description that the HAZOP method brings to bear considerable structural rigor. It breaks down the entire process into a large number of discrete sections (typically pipe runs from Point A to Point B and individual vessels) and goes through an extremely repetitive exercise to examine deviations in significant detail. Most deviations will not, in fact, identify any significant vulnerabilities, one reason that HAZOPs for large processes are conducted over multiple days. The exercise simply takes time. Attempting to move swiftly through it tends to create an overload effect that defeats the purpose of this method.

The strengths of the HAZOP method are thoroughness enforced by structural rigor, focus at even small levels of detail, adaptability to almost any process or activity, and generation of an organized evaluation record as an intrinsic part of the methodology. HAZOP also forces participants to properly define the process or activity at a detail level prior to beginning. Weaknesses include the fact that HAZOP is much more time and resource intensive than other methods. It is also vulnerable to poor initial organization. HAZOPs generally represent overkill for simple processes and predominantly manual activities, but are ideal for more complex processes, where the sheer magnitude of the potential deviations can overwhelm a "what if" examination.

Table 2-5 presents a simple HAZOP example for the Metal Dissolution Process (Figure B.8) in the Plutonium Recovery Facility defined in Appendix B of DOE-HDBK-3010-94. The parameter examined is "Flow." Compared to the previous "what if" examples, the rigorous and repetitive nature of the method is clear. "What if" relies on the ability and experience of the analysts to insure completeness; HAZOP relies more on the method's formal structure.

As noted previously, Table 2-5 is not an example of the hazard evaluation table expected in an actual DSA. The HAZOP identifies process vulnerabilities and interactions from which a set of hazard scenarios are derived. For example, a runaway exothermic reaction generating hydrogen is an event that would be expected in the DSA hazard evaluation table. Depending on the HAZOP results, there could be multiple entries for the same event to identify different progression paths, some of which would be of concern and others which might not. Alternatively, one entry could cover all potential progression paths. In that event, all paths are still assessed to determine which, if any, warrant specific control. It may be that the hydrogen detector and shutdown interlock is adequate to credit for all scenarios. It may also be that an individual control in a specific progression path requires crediting as well, either due to the high likelihood of that progression path or its ability to minimize the effect of the hydrogen detector and associated interlocks. For example, suppose the spray chamber was sized so that one scenario allowed a large amount of acid reactant to remain in the chamber. In that event, simply securing acid flow might not be adequate to prevent hydrogen gas generation and accumulation.

It is significant that these methods were not developed to credit SSCs. They are intended to challenge the design. Therefore, use of a complex methodology such as HAZOP is not focused exclusively on developing a DSA hazard evaluation table. The methodology (or any HA methodology) may uncover safety issues that need to be addressed. For example, if scenarios exist where hydrogen continues to be generated at an accelerated rate in the spray chamber even after the hydrogen detector interlocks secure acid flow, process improvements may be necessary. In that event, the air sparge into the spray chamber could be replaced by a nitrogen sparge.

Table 2-5. HAZOP Example.

Note: Piping from Heat Exchanger to Spray Chamber (DOE-HDBK-3010-94 Figure B.6)

Parameter	Deviation	Cause	Consequence	Safeguards	Comments/Actions
Flow	No	1. Pump not working 2. Heat exchanger outlet valve incorrectly positioned 3. In-line filter clogged	Operational	Return line flow meter, Temperature sensors	Safe Condition: Dissolution reaction ceases without fresh acid flow Unsafe Condition: Potential to pressurize heat exchanger
Flow	No	1. Piping rupture	Plutonium solution spill	Glovebox, Glovebox ventilation, Critically safe drainage basin, Room air monitor, Room ventilation	
Flow	Low	1. Pump impaired 2. Heat exchanger outlet valve incorrectly positioned 3. In-line filter clogged	Temperature transient (less flow is heated more)	Temperature sensor on slab tank, Steam inlet control, Return line flow meter	Safe Condition: Lower flow minimizes reaction Unsafe Condition: Excess acid temperature can dissolve an undesired impurity
Flow	Low	1. Piping leak	Plutonium solution spill	Glovebox, Glovebox ventilation, Critically safe drainage basin, Room air monitor, Room ventilation	
Flow	High	1. Pump output excessive 2. Heat exchanger outlet valve incorrectly positioned	Temperature transient (more flow is heated less)	Temperature sensor on slab tank, Steam inlet control, Return line flow meter, Hydrogen detector, Shutdown interlocks, Air sparge	Unsafe Condition: More flow maximizes reaction. Unsafe Condition: Low acid temperature can yield undesired hydride sludge.
Flow	Wrong	1. Steam inlet off with heat exchanger leak	Plutonium solution enters HX condensate	Condensate collected in Raschig ring tank, condensate samples	Action: Verify sampling frequency

2.4.3 FAILURE MODES AND EFFECTS ANALYSIS

The failure modes and effects analysis (FMEA) is a methodology focused on individual component or subcomponent failures. Failures are postulated, with the resulting effects on a larger component or system assessed. For example, if looking at a process, one could start with a pump. The pump can fail on, fail off, leak, etc. These are the failure modes. The causes of each failure mode, the consequences to the larger system for a given failure mode, and associated preventive and mitigative controls are identified. One can also, however, do an FMEA on the pump alone. In that case, failure modes of subcomponents are postulated and evaluated in terms of their effect on pump operability. FMEA was historically of great value in the airline industry, where it was desired to identify failure modes with catastrophic potential for a plane in flight.

As can be seen from the description above, FMEA is a simple, flexible tool for examining equipment failures. It is ideal for simple processes or when the need arises to characterize the performance spectrum associated with individual pieces of equipment. The method itself is intuitive, similar to “what if,” but with greater structural rigor. It is, however, prone to structural gaps in certain applications. FMEA does not generally handle a broad spectrum of human errors, nor does it generally handle quality and composition issues, such as process chemistry deviations. Lack of experience with the methodology can also lead to a narrow focus on individual failures as opposed to integrated process behavior.

Consider again the Metal Dissolution Line in the Plutonium Recovery Facility in Appendix B of DOE-HDBK-3010-94. A simplistic FMEA example assessing the hydrogen detector as one component of an overall process is provided in Table 2-6. This example FMEA would be or primary use in assessing the reliability of the hydrogen detector for the usage proposed.

Table 2-6. FMEA Example.

Process: Metal Dissolution Line Component: Hydrogen Detector

Failure Mode	Effect	Safeguards	Comments/Actions
High	Generates premature process shutdown for low H2 concentration	Indication on operational console, Shutdown interlock.	Fail safe
Low	Failure to generate process shutdown when required	Indication on operational console, Spray chamber temperature sensor (also feeds shutdown interlock), Temperature indications on operational console	Unsafe condition Increased hydrogen concentrations are generally accompanied by higher temperatures. A runaway exotherm would still yield a shutdown. However, conditions short of that could yield H2 concentrations in excess of the shutdown limit.
As is	Failure to generate process shutdown when required	See "Low"	See "Low"
Loss of Power	Triggers shutdown interlock	Indication on operational console, Shutdown interlock.	Fail safe
Signal to Interlock, Mode A	Triggers shutdown interlock	Indication on operational console, Shutdown interlock.	Fail safe
Signal to interlock, Mode B	Failure to generate process shutdown when required	See "Low"	See "Low"

2.4.4 EVENT TREES AND FAULT TREES

Event trees and fault trees are formal logic constructs designed to document progression paths for an event. Event trees utilize inductive reasoning while fault trees utilize deductive reasoning. These two tools can be combined in a formal quantitative or probabilistic risk assessment, but such an assessment for an entire facility or process is not typical when evaluating DOE nonreactor nuclear facilities. Event trees and fault trees are normally used in DSAs as support tools to illuminate a specific issue of interest.

Inductive reasoning is often characterized as "bottom-up" logic since it starts with a specific premise and moves toward a general conclusion. An event tree correspondingly starts with a specific initiating event and moves toward a broad collection of potential outcomes. A simple example of an initiating event might be "loss of cooling water to a furnace." Every action that can result from that event then forms a decision point from which multiple possible outcomes branch. For example, suppose Alarm A is supposed to sound to generate an operator response if cooling flow is lost. The first decision point is therefore "Alarm A functions." Two branches stem from that point: (a) if alarm A functions, the progression moves to a decision point labeled "Operator responds;" (b) if Alarm A does not function, operator response is initially bypassed and the resulting branch moves to a different decision point. The end result is a complete spectrum of outcomes, from successful to unsuccessful to catastrophic, which are characterized in terms of actions and controls associated with their progression. Each individual path through this event tree represents a separate event sequence. Thus, the minimum cut sets that yield failure of the system or its safety function can be defined.

Deductive reasoning is often characterized as "top-down" logic since it uses general premises to arrive at a specific conclusion. A fault tree thus begins with the undesired end state. Such end states have often been identified by application of other hazard evaluation methodologies. For demonstration purposes, a simple example of an undesired end state is "the car does not start." The next step down in the fault tree lists the immediate causes for that result (e.g., starter motor failure, spark plug failure, lack of gas in cylinder). The next step down lists all the potential causes for each cause above (e.g., gas not in cylinder can be caused by no gas in tank, failure of fuel pump, line leak). These potential failure mechanisms are joined by "AND" or "OR" gates depending on whether multiple mechanisms (A "AND" B) are needed to cause the failure above or if a single mechanism (A "OR" B) suffices. This process ends either in basic occurrences that cannot be subdivided further or at a predetermined evaluation boundary. Again, the minimum cut sets that yield failure of the system or its safety function can be defined.

The strengths of these methodologies include logical rigor, recording of results in a branch structure as the evaluation occurs, and direct support of numerical estimation of likelihood of the postulated significant consequences. Weaknesses include a tendency toward tunnel vision if the failure mode or safety function of interest is not precisely defined, as well as a significant resource and time investment to generate integrated results.

2.4.5 NUCLEAR CRITICALITY HAZARD EVALUATION

An inadvertent criticality accident represents a special case for hazard evaluation. The criticality safety program requirements[3] are derived from the HA process established in the American National Standards Institute/American Nuclear Society (ANSI/ANS)-8 series of national standards (e.g., ANSI/ANS-8.1, *Nuclear Criticality Safety in Operations with Fissionable Material Outside Reactors*), which require a documented criticality safety evaluation demonstrating that operations with fissionable material remain subcritical under both normal and credible abnormal conditions. These criticality safety evaluations provide the technical basis to establish controls to prevent or mitigate nuclear criticalities, and are implemented by the criticality safety program.

Information on what is included in the DSA hazard evaluation is provided in DOE-STD-3009-2014, Section 3.1.3.2, Criticality Hazards. For example, it addresses a discussion of a criticality accident alarm system if required by the nuclear criticality safety program, and it establishes a limited set of inadvertent criticality scenarios to be considered in the DSA hazard evaluation. In general, an inadvertent criticality has the potential for significant consequences to the facility worker, low consequences to the offsite public, and may or may not have significant consequences to the co-located worker at 100 m depending on the type of criticality and any shielding present. Safety classification of preventive or mitigative controls as identified in the DSA hazard evaluation is performed as described in DOE-STD-3009-2014 Section 3.3.4, Criticality Safety Controls, and will in general result in one or more criticality controls for the limited set of scenarios evaluated in the DSA hazard evaluation being designated as SS and have coverage in the TSRs.

[3] Criticality safety program requirements are established in DOE O 420.1C. This Order states that DOE-STD-3007-2007 is the required method for performing criticality safety evaluations, unless DOE approves an alternate method.

Only a few evaluations of criticality scenarios for a facility need to be carried to dose consequence calculations for the co-located worker and offsite public and documented in the DSA to support the safety classification of criticality controls. Appendix I provides guidance to the Nuclear Safety and Criticality Safety analysts for the consequence analysis of criticality accidents and estimation of source terms for subsequent radiological consequence analyses to receptors of interest for the DSA.

2.4.6 CHEMICAL HAZARD EVALUATION

As discussed in Section 2.2.4, chemical hazards are screened to determine the need for further hazard evaluation. Chemicals that are screened out in this manner still need to be considered for their possible impact on radiological or other chemical accident initiation or progression, or have the ability to impact the safe operation of the facility (e.g., inability to perform a SAC). Chemical properties such as reactivity, toxicity, and incompatibility with other chemicals are included in the hazard evaluation.

Qualitative evaluation of chemical consequences using any of the hazard evaluation techniques discussed above is generally sufficient to provide a basis for comparison to consequence thresholds of interest for the selection of SS controls, discussed in the next section. However, for some situations, further quantitative analysis of consequences is necessary for control selection. For example, see DOE-STD-3009-2014 Section 3.2.3.3, Chemical Hazards, and its Section A.2 of Appendix A for further information. Later chapters of this Handbook will provide guidance on quantifying chemical source terms and dispersion analysis to estimate concentrations to downwind receptors.

2.5 QUALITATIVE RESULTS FROM THE HAZARD EVALUATION

The industry hazard evaluation methods discussed above evaluated process upsets, equipment failures, human errors, and potential safety features. Table 2-7 show how this information can be utilized to start development of a hazard evaluation table for the DSA.

Table 2-7. Initial Development of Hazard Evaluation Table.

Event No.	Event Cat.	Event Description	Causes	Preventive Features	Mitigative Features
S-xx	E-6	Vehicle impact to facility/containers Location: Building xxx Release Mechanism: Impact and spill MAR: 10 kg PE-239 Initial Condition: TRU waste in metal containers	Vehicle accident: Operator error (excessive speed, inattention) Operator illness/incapacitation (e.g., heart attack) Mechanical failure of vehicle Improper maintenance on vehicle	**SSCs:** Concrete vehicle barriers **Administrative:** Transportation Safety Program (establish speed limits on site roads, training) Vehicle maintenance program	**SSCs:** TRU waste packaging for stored waste (IC) **Administrative:** Emergency Preparedness Program (emergency response activities); Procedures and Training Program (workers trained to evacuate)

The next step is to perform a qualitative estimate of the unmitigated consequence, likelihood, and optionally risk ranking of the hazard scenarios. The DSA hazard evaluation is based on an unmitigated and mitigated analysis that derives the selection of hazard controls. An unmitigated hazard scenario is evaluated for each initiating event by assuming the absence of preventive and mitigative controls.

This information is then captured in a hazard evaluation table that builds upon the information in Table 2-7 (See example in Table 2-11 presented later in this section).

Initial conditions may be necessary to define the unmitigated evaluation; further guidance is discussed in Section 3.3, Analysis Inputs and Assumptions.. The consequences and the likelihood of the unmitigated hazard scenario are estimated (using qualitative and/or semi-quantitative techniques). DOE-STD-3009-2014 Section 3, "Hazard Analysis, Accident Analysis and Hazard Control Selection Criteria and Guidance," provides additional discussions on requirements and guidance for unmitigated analysis and control selection for the mitigated analysis. The following provides a high-level summary of estimating unmitigated consequence and likelihoods, then presents information for qualitative evaluation of consequences, likelihoods, and risks, and control identification.

Unmitigated likelihood and consequence estimates assume that active engineered and administrative controls are not available to reduce either the consequence or likelihood of the hazard scenario. However, the unmitigated analysis does assume that passive design features exist and provide their safety function. In addition, the unmitigated analysis considers facility geometry and physical plausibility, and evaluates the unmitigated likelihood and consequence accordingly For example, in an explosion scenario, the unmitigated likelihoodwould not be reduced by an engineered control, such as a vessel purge. However, the unmitigated likelihood of the explosion could be reduced based on how difficult it is for the explosion scenario to develop; e.g. there must be specific conditions in the container, combined with a leak from the container, combined with extreme human error, for explosion to occur. Additional requirements and guidance on unmitigated analysis is provided in Section 3.2.2 of DOE-STD-3009-2014.

2.5.1 QUALITATIVE CONSEQUENCE

Table 2-8, reproduced from Table 1 of DOE-STD-3009-2014, provides qualitative consequence thresholds (bins) to estimate potential effects on facility workers, co-located workers, and the public (maximally-exposed offsite individual [MOI]). This is similar to consequence level thresholds defined in DOE-STD-3009-94 CN3. High, moderate and low consequence levels are quantitatively defined for the offsite public and co-located workers. High consequence levels are qualitatively established for facility workers consistent with DOE-STD-3009 guidelines for a significant worker consequence. Moderate and low consequence levels are not defined for facility workers, because qualitative analysis would not yield results that provide a meaningful comparison to a distinguishable threshold[4].

[4] Mitigated analysis that credits controls to reduce unmitigated high consequences generally show mitigated low consequences on the DSA hazard evaluation table.

Table 2-8. Consequence Thresholds.

Consequence Level	Public[1,4]	Co-located Worker[2,4]	Facility Worker[3]
High	≥25 rem TED[5] or ≥PAC[6]-2	≥100 rem TED or ≥PAC-3	Prompt death, serious injury, or significant radiological and chemical exposure.
Moderate	≥5 rem TED or ≥PAC-1	≥25 rem TED or ≥PAC-2	No distinguishable threshold
Low	<5 rem TED or <PAC-1	<25 rem TED or <PAC-2	No distinguishable threshold

[1] MOI - A hypothetical individual defined to allow dose or dosage comparison with numerical criteria for the public. This individual is typically located at the point of maximum exposure on the DOE site boundary nearest to the facility in question (ground level release), or may be located at some farther distance where an elevated or buoyant radioactive plume is expected to cause the highest exposure (airborne release).

[2] A co-located worker at a distance of 100 m from a facility (building perimeter) or estimated release point.

[3] A worker within the facility boundary and located less than 100 m from the release point.

[4] Although quantitative thresholds are provided for the MOI and co-located worker consequences, the consequences may be estimated using qualitative and/or semi-quantitative techniques.

[5] Total Effective Dose (TED), 50-yr commitment.

[6] DOE's Protective Action Criteria (PAC) are defined by Advanced Technologies and Laboratories International, Inc in "Protective Action Criteria (PAC): Chemicals with AEGLs (Acute Exposure Guideline Level), ERPGs (Emergency Response Planning Guidelines), & TEELs (Temporary Emergency Exposure Limit)", Rev 27, February 2012. This is available at: http://www.atlintl.com/DOE/teels/teel.html

Scoping estimations of impacts to facility workers, co-located workers, and the MOI may also be appropriate to assign qualitative consequence levels. Consequence estimation is typically performed differently for facility workers that may be near the source of the event or other areas within the facility where exposure may occur, as opposed to other workers or the public located at a distance from the facility. The latter often has a semi-quantitative basis. That is, it is a straight forward exercise to identify radioactive materials of greatest concern downwind using specific activity and dose equivalents that also incorporate the dispersion analysis. Likewise, chemicals that combine significant volatility and toxicity are easily identified. The safety analyst therefore starts with a short list of materials and release scenarios that are bounding. Bounding is intended to refer to the accident with the highest consequences among a group of similar accidents.

It is a simple matter to calculate "unit release" consequences at any distance of concern (within the capabilities of dispersion tools being used) to yield "rules of thumb" for screening calculations such as rem/Curie released or concentration/mass released. These in turn are used to qualitatively scale given events into qualitative consequence bins or levels of severity (e.g., high, moderate, low).

Facility worker consequences have no such simple metric. It is obvious that releasing large amounts of a toxic substance (e.g., hydrogen fluoride) quickly from a vessel failure can have fatal consequences. But more limited releases historically do not yield such dire consequences. It is important that local worker consequences be evaluated with some sense of perspective and experience, as it is possible to imagine unrealistic events in ways so severe that no control set conducive to worker proximity exists. DOE-HDBK-3010-94 speaks to precisely this issue when discussing ARF and RF values:

> *"The use of the word "reasonable" is an acknowledgement that the only definitive bounds are ARFs and RFs of 1.0, which can always be postulated if enough synchronous, extreme localized conditions are assumed. Such extreme synchronicity is neither an expected condition nor a practically useful model of reality."*

In effect, the safety analysis should focus on the work area(s) in which accidents release hazardous/radioactive material and the associated concentrations of such releases without reliance on specific assumptions about worker placements, hypothetical work area volumes for mixing of the release, or duration that workers may be exposed. It is important not to deliberately underestimate unmitigated consequence potential, but it is also important to not exaggerate unmitigated consequences relative to historical experience to a point where every exposure to the local facility worker is a high consequence event. On the other hand, a "see and flee" approach that results in low consequences should not be assumed without due consideration of the accident characteristics.

To ensure an informed and defensible qualitative evaluation, the determination of facility worker consequences is based on a combination of the following:

- The magnitude, type, and form of radioactive and hazardous materials involved in a hazard scenario;
- The type and magnitude of energy sources involved in a hazard scenario;
- Characteristics of the hazard scenario such as duration and the location where it may occur (e.g., in unmanned areas such as tank vaults); and,
- The potential for a hazard to impact workers' mobility or ability to react to hazardous conditions.

Related to this last bullet some additional discussion is warranted. The intent of the last bullet is to provide some realism into the event scenario for a "reasonable" unmitigated estimate of potential consequences to the facility worker. Although unmitigated analysis may not take credit for administrative controls or active engineered features, it is reasonable to assume that facility workers have some knowledge of the facility hazards and fundamental training to react to hazardous situations (assuming the characteristics of the accident aren't disabling, provide obvious warning signs, and are slow developing to allow workers time to react). As such, it is not necessary to model exposures using quantitative factors or assuming stationary placement of workers directly with plumes (e.g., an entire shift).

DOE-STD-3009-2014 states that "The facility worker's mobility or ability to react to hazardous conditions should not be used as the sole or primary basis for determining facility worker impacts." This means that all four of the factors listed above need to be considered together, not individually. As an example, an assumption that a worker within a building is unaffected by release from a building fire based on hazard recognition and timely evacuation would have to consider the location and characteristics of the fire relative to radioactive or hazardous material that may be affected by the fire (considering quantity, form, and dispersibility).

In evaluating the unmitigated consequences associated with a postulated hazard scenario, the following potential contributing elements may be important considerations when addressing the above four bullets:

- Timing of radiological release: Hazard scenarios involving fires can develop quickly, but not so rapidly as to preclude evacuation as an effective mitigative measure; other scenarios, like criticality, explosion, and instantaneous releases from confinement enclosures or containers can entail significantly more rapid radiological exposure. Another example is a long duration release such as during a spill of a radioactive or hazardous chemical liquid where a worker in the vicinity of the spill would not be expected to stand in the spilled liquid for an extended period of time. Therefore, though some exposure might occur, a conservative but reasonable time of exposure should be assumed.
- Hazard warning: The availability of obvious hazard warning and its timing relative to significant radiological exposure may impact facility worker consequences. Warning may be provided by the event itself (e.g., fire smoke, drum lid displacement), however, engineered detection and notification systems [e.g., Continuous Air Monitors (CAMs), fire alarms] are not credited for the unmitigated analysis. It is not reasonable to assume that a worker would remain in a room subject to flashover or toxic concentrations from a major fire in order to receive a significant radiological or hazardous chemical exposure. In making these evaluations for the facility worker, additional considerations include:
    - If the facility worker would reasonably be aware of the event's occurrence, and could take self-protective actions after the event occurs to protect themselves from a fatality or serious injuries from the non-radiological or non-hazardous material consequences, assume that the facility worker immediately takes self-protective actions to reduce potential unmitigated consequences.
    - In cases where the facility worker would not be reasonably aware of the event's occurrence (e.g., characteristics of the release such as no odors, no visibility of plumes or smoke, occurrence in areas that could mask the release), there is no specified period of exposure, such as two hours. Consider reasonable lengths of time the facility worker would normally be present based on the nature of planned activities.
- Scenario impact on protective action capability: Hazard scenarios involving explosions and NPH-initiated failure of buildings or equipment can cause damage to structures or injury to personnel impeding egress; thus, increasing potential radiological consequences.
- Potential exposure magnitude: Severity of radiological uptakes or chemical exposures are a function of the magnitude of the energy associated with the accident scenario, the quantities of material estimated to be released, and the pathways for transport to and absorption by workers; inhalation is typically the dominant exposure pathway, though skin exposures to small quantities of some chemicals such as aqueous hydrofluoric acid can be fatal.
- Location: The impact to facility workers could be affected by whether or not the accident being evaluated occurs inside or outside of buildings or structures. For releases outside of structures, consider the qualitative impacts on dose of the plume moving past the facility worker. For releases inside a nuclear facility, consider whether the release is being mixed within a relatively small work area volume such as with glovebox operations or into a large open area such as waste container staging buildings.

As a general rule of thumb application of the above considerations, examples of high unmitigated radiological consequences to the facility worker are: (1) explosions, pressurized powders or high-concentration liquid sprays, and other energetic events that impact large quantities of radioactive material are considered to cause significant radiological exposure to the facility worker due to the rapid nature of the event, the resulting source term, and the inability of the worker to take protective action (i.e., evacuate) prior to receiving a substantial dose (a similar analogy can be established based on hazardous chemicals and toxicological consequences); and (2) criticality events based on the prompt dose received

and the potential for no indication that a criticality has occurred until after the event. Other types of events such as fires, spills, or drops of containers require more careful evaluation of the characteristics of the actual accident event (e.g., location effects on workers, time to develop, magnitude of release).

Facility worker consequences, due solely to a SIH, do not need to be categorized in the hazard evaluation if screened out per Section 2.3.3. However, the evaluation of radiological or chemical hazards (e.g., uranium-water reaction generating hydrogen gas resulting in a potential explosion and shrapnel of the vessel or piping, or radiological waste processing stream containing sodium hydroxide that spills and results in significant chemical burns) that result in a prompt death or serious injury would be assigned a high consequence per Table 2-8. For the physical consequences to the worker (i.e., potential serious injuries or fatalities), the event is assessed to determine whether the physical hazard associated with initiating or worsening a radiological or hazardous chemical accident is a SIH or if it should be assigned a high consequence level for further consideration of the need for SS controls. The primary consideration in determining whether the physical hazard is a SIH is if the regulated material (i.e., radiological or chemical material) is not a primary cause or major contributor to the hazardous event, and that it is adequately addressed by 10 CFR 851, 10 CFR 835, *Occupational Radiation Protection*, and Integrated Safety Management System HA requirements, as implemented by the DSA/TSR commitment to the facility's safety management programs. The following examples of not assigning consequences based on SIH considerations are provided for transuranic (TRU) waste container operations, where the physical consequences to the worker are grouped by the source of the physical consequences' thermal hazards, explosions, missiles, material and equipment movement, asphyxiants, and other impacts.

- **Thermal hazards** to the worker are due to welding equipment and combustible or flammable material fires ignited by typical ignition sources (e.g., electrical or thermal). The welding torch is a common SIH throughout various industries. The fires with typical ignition sources are also SIHs because the hazard and potential physical consequences are due to common types of equipment found throughout various industries. Both of these events are adequately regulated by OSHA and national consensus standards.
- **Explosions** are due to flammable gases with welding equipment, other equipment explosions (e.g., battery charging, refueling), or waste container explosions. The welding and equipment explosion and potential physical consequences are considered a SIH because these events commonly occur in general industry and are adequately regulated by OSHA and national consensus standards. Although the hazard associated with pressurized drums is regulated by OSHA hazardous waste operations requirements, a high consequence level should be assigned for the waste TRU container explosions because the primary hazard is due to the regulated material (radiolysis or chemical reactions).
- **Missiles** are caused by an equipment explosion (e.g., battery explosions), failure of pressurized or mechanical system (e.g., air compressor, gas bottle, fans, and motors), compressed gas cylinder failures, over-pressurization or deflagration of a waste container, or extreme winds and tornadoes. Missiles are considered a SIH because these events commonly occur in general industry and are adequately regulated by OSHA and national consensus standards.
- **Equipment-related events** including vehicle/equipment load drops are SIHs because the hazards are presented by the equipment used in the work process, and the events are not caused by the regulated material. These events are adequately regulated by OSHA and national consensus standards.
- **Material and equipment movement** is a hazard presented by moving, lifting, dropping, vehicle-impact-induced movement, collapse due to corrosion/degradation, or movement due to a seismic event. The hazard is due to the size and mass of the object being moved and is not a hazard

presented by the regulated material. The same hazard exists in various industries, such as construction. These events are adequately regulated by OSHA and national consensus standards.

- **Asphyxiant hazards** are presented by the use of nitrogen and P-10 gas associated with loading or unloading shipping casks; acetylene or other compressed gases for maintenance activities and liquid nitrogen dewers for assaying waste containers; and carbon monoxide buildup from material handling vehicles inside a facility. These hazards are common in various industries, and are adequately regulated by OSHA and national consensus standards. Smaller amounts of gases (i.e., nitrogen or argon) present for equipment calibration are in quantities that do not present an asphyxiation hazard.
- **Other impacts** encompass collisions from vehicles traveling on the site (e.g., forklifts, trucks), external vehicles, and potential site aircraft crashes. These hazards exist in everyday life and are accepted by the public. Although no specific controls may be identified for these SIHs, the safety management programs, which govern the conduct of activities involving various industrial hazards, will provide protection to the worker for these hazards.

The qualitative evaluation for the facility worker may be supported by scoping calculations, engineering judgment, and historical experience. This qualitative approach is used because quantitative estimates are sensitive to a variety of possible assumptions such as facility worker position, circumstance, and close proximity to the point of release. Consequence estimates can rely on experience or can be determined from: (1) simple source term calculations, (2) existing safety documentation, and/or (3) qualitative assessment supported by calculations.

Qualitative judgment is inevitable in hazard evaluation. It is routinely utilized in industries outside DOE. *Guidelines for Hazard Evaluation Procedures* (CCPS, 2008) noted the following:

> *"The subjective nature of these deliberations may trouble some people who use the results of these studies because this subjectivity creates a lack of confidence in the results. Some people incorrectly believe that if the analyst uses quantitative methods to express the significance of a problem, then the limitation of subjectivity will simply fade away. However, this is not the case. The apparent numerical precision of a QRA[5] can mask (1) a great deal of the judgment that influenced the selection of accident models and (2) large uncertainties associated with the data used to estimate risk."*

[5] Quantitative risk assessment or quantitative risk analysis

Estimating consequences qualitatively requires consistent assignments of the severity level for similar scenarios. This may require "normalizing" hazard scenarios by comparing against one another for consistent assignment of a severity level and to verify no outliers exist absent a sound explanation. In addition, for those hazard scenarios that are selected as representative or unique accidents for further quantitative accident analysis, insights from that quantitative analysis should be used to verify the qualitative consequence assignments for the hazard evaluation.

2.5.2 QUALITATIVE LIKELIHOOD

Likelihood of a hazard or accident scenario is typically assigned to qualitative bins defined by guidelines aided with numerical ranges of two-orders-of-magnitude or more. That is typically perceived as more accommodating of uncertainty so long as similar events are assigned similar likelihoods. Table 2-9, reproduced from Table 2 of DOE-STD-3009-2014, provides qualitative likelihood bins.

Table 2-9. Qualitative Likelihood Classification.

Description	Likelihood Range (/year)	Definition
Anticipated	Likelihood $>10^{-2}$	Events that may occur several times during the lifetime of the facility (incidents that commonly occur).
Unlikely	$10^{-2}>$likelihood $>10^{-4}$	Events that are not anticipated to occur during the lifetime of the facility. Natural phenomena of this likelihood class include: Uniform Building Code-level earthquake, 100-year flood, maximum wind gust, etc.
Extremely Unlikely	$10^{-4}>$likelihood $>10^{-6}$	Events that will probably not occur during the lifetime of the facility.
Beyond Extremely Unlikely	Likelihood $<10^{-6}$	All other accidents.

Although the exercise of determining accident likelihood is typically qualitative, analysts often develop a numerical basis for judgments to provide consistency. For example, a simple methodology for unmitigated likelihood assignment could be to assign a probability of "1" to non-independent events, "0.1" to human errors, and "0.01" to genuinely independent SSC failures that would be used to establish the initiating event likelihood [6] as described on Table 2-9. For the unmitigated analysis, these human errors and equipment failures cannot represent the failure probability of a preventive control that would otherwise provide a SC or SS safety function. Another methodology for unmitigated initiating event likelihood classification would be to use a summary of historical data.

Conservative values are assessed to accommodate uncertainties in frequency levels (Anticipated (A), Unlikely (U), Extremely Unlikely (EU), and Beyond Extremely Unlikely (BEU)). This practice is particularly important when an event frequency is just below the next highest frequency level. For example, 9.7E-3/year is at the high end of the U frequency level. Considering the sources, methods, and uncertainty associated with this value, this event may be considered to have a frequency level of A rather than U.

[6] To determine the likelihood of an accident scenario, only initiating events are expressed as rate of occurrence with the units of inverse time (i.e., per year), and other enabling events are expressed in terms of unitless failure probabilities.

The mitigated frequency of occurrence when crediting preventive controls could also apply simple numerical estimates (e.g., 0.01 failure probability of a preventive engineered control or a preventive SAC depending on the confidence as justified in the DSA Chapter 4 on safety SSCs and SACs) to assign a lower unmitigated frequency bin (e.g., to lower by one qualitative classification from unlikely to extremely unlikely).

Similar to the process for assigning qualitative consequences, estimating likelihoods qualitatively requires consistent assignments of the likelihood bins for similar scenarios. This may require "normalizing" hazard scenarios by comparing against one another for consistent assignment of a likelihood and to verify no outliers exist absent a sound explanation.

2.5.3 QUALITATIVE RISK

The primary purpose of risk ranking/binning is to support the selection of design/evaluation basis accidents (D/EBAs) and hazard controls for further quantitative accident analysis. Risk ranking is predetermined based on the risk matrix used. That is, a given likelihood and consequence directly translate into a specified qualitative risk level (sometimes called risk category). Table 2-10, reproduced from Table 3 of DOE-STD-3009-2014, provides an example of a risk ranking table that combines likelihood and consequence.

Table 2-10. Qualitative Risk Ranking Bins.

Consequence Level	Beyond[7] Extremely Unlikely Below 10^{-6}/yr	Extremely Unlikely 10^{-4} to 10^{-6}/yr	Unlikely 10^{-2} to 10^{-4}/yr	Anticipated Above 10^{-2}/yr
High Consequence	III	II	I	I
Moderate Consequence	IV	III	II	II
Low Consequence	IV	IV	III	III
Risk Category I = Combination of conclusions from risk analysis that identify situations of major concern Risk Category II = Combination of conclusions from risk analysis that identify situations of concern Risk Category III = Combination of conclusions from risk analysis that identify situations of minor concern Risk Category IV = Combination of conclusions from risk analysis that identify situations of minimal concern				

Beyond the qualitative application of consequences and likelihoods (or supplemented with quantitative perspectives) for the hazard evaluation, risk ranking serves the broader purpose of confirming for the DOE approval authority that the overall mitigated risk of facility operation is low. Risk ranking can also highlight a given scenario whose mitigated risk remains significant. Additional guidance on use of unmitigated risk estimates for control selection is provided in Chapter 8, *Hazard Control Selection and Classification*.

[7] For external events, likelihood below 10^{-6}/yr conservatively calculated is "Beyond Extremely Unlikely".

2.6 CONTROL IDENTIFICATION DURING THE HAZARD EVALUATION

Control identification occurs as part of the hazard evaluation and is captured in the hazard evaluation table where potential means for preventing or mitigating the hazardous event are captured. The most important controls for the higher unmitigated consequence or risk events are then selected to prevent or mitigate the hazard scenario. The benefit of the control as far as changing the risk category of the event is typically also captured in the hazard evaluation table. The classification of the hazard controls (as SS or SC) is discussed in Chapter 8, *Hazard Control Selection and Classification*, of this Handbook.

The process of designating one or more controls as SS or SC is judgment-based and depends on multiple factors, such as: hierarchy of available controls, the control's effectiveness, and relative reliability of selected controls. If the selection of sufficient preventive controls does not eliminate the hazard or terminate the accident scenario and prevent a release of radioactive or other hazardous materials, then an iterative process of mitigative control selection should be performed. This involves taking credit for mitigative features incrementally and comparing the results to the evaluation criteria until below it. The extent of reduction in dose consequences is a function of the effectiveness of the mitigative control, such as high efficiency particulate air (HEPA) filters, or reduction in MAR.

2.7 HAZARD EVALUATION PRESENTATION IN DSA

The analyst uses insight from the industry hazard evaluation methods such as HAZOPs to create a separate DSA hazard evaluation table or data sheets, and results for the unmitigated and mitigated hazard analyses are presented in the DSA hazard evaluation section as discussed in the DSA Section [3.3.2.3], Hazard Evaluation Results, as presented in Section 4 of DOE-STD-3009-2014. Additional information for a Preliminary Hazard Analysis (PHA) for a safety design basis document is included in Appendix A.

The DSA hazard table or data sheet has certain essential characteristics. First, if multiple types of operations are occurring, it normally breaks the hazard evaluation table into separate sections so that each section presents one clearly defined type of operation, or has multiple data sheets developed for a single type of operation. For example, glovebox operations could be segregated from handling operations outside of gloveboxes. Or furnace operations could be segregated from liquid processing operations. Or a scrap recovery line could be segregated from a product line. The critical point is to provide a comprehensible structure to the presentation. Absent that, multiple types of hazard scenarios may be inappropriately combined together, thereby losing control distinction, or the approach may simply not communicate in an effective manner to outside reviewers.

Second, the specific hazard scenarios are clearly stated. For example, a HAZOP may have dozens of entries for parameter-guide word combinations. These need to be turned into discrete events. A HAZOP may note that low flow caused by incorrect positioning of valves upstream has no major effect on a process other than operational disruption, while low flow due to a large leak represents a significant operator hazard. Those are two entirely different events. Blurring them together will give the appearance that TSR controls are needed for a nonhazardous event. Or conversely, it could lead to inconsistent or nonconservative consequence estimation for an event that does require TSR controls. Again, the knowledge of process vulnerabilities gained using standard hazard evaluation techniques is used to construct a DSA hazard evaluation presentation that identifies individual events in an organized and comprehensible fashion.

Third, potential preventive or mitigative controls are identified. Next, unmitigated and mitigated consequences are clearly identified in order to support SS and SC designation. Likelihood estimation is expected as well in DSA hazard evaluation. That is another reason not to blur multiple initiators together.

Finally, DSA hazard evaluations combine consequence and likelihood into risk estimations that inform control selection. For example, an unmitigated high consequence event at a likelihood of anticipated may require additional preventive controls than an unmitigated high consequence event with a likelihood of extremely unlikely. Or, to use another extreme, an event may have been identified for inclusion in the hazard evaluation but ultimately deemed not physically plausible, or for external events such as an aircraft crash, is less than the likelihood screening criteria from DOE-STD-3014-96, *Accident Analysis for Aircraft Crash into Hazardous Facilities*. In that case it would have an assigned frequency of beyond extremely unlikely and is shown on the hazard evaluation table as not being a significant risk.

Table 2-11 presents an example hazard evaluation table for presentation in the DSA showing both the unmitigated and mitigated analysis, which builds upon the example provided in Table 2-7. There are many different formats that can be used, e.g., a hazard evaluation data sheet for each hazard scenario, as long as it meets the need for a comprehensive hazard evaluation to provide an unmitigated analysis of hazard scenarios in terms of potential consequences, their likelihoods, and identification of preventive and mitigated controls, and optionally, to also present the mitigated analysis that credit safety controls. The mitigated hazard evaluation can be included as additional columns as shown on Table 2-11, or another convention is to use separate rows for the unmitigated and mitigated evaluations. Appendix A provides an example of information to be presented on a hazard evaluation table for safety design basis documents.[8]

The important point to keep in mind is that the DSA hazard evaluation is not a compendium of raw results. It is intended to tell the story of how the TSR control set derived addresses the potential vulnerabilities of an operation or activity. This story needs to demonstrate it is both complete and reasonable. The hazard evaluation methodologies applied in the chemical and other industries discussed above do not generate a raw product designed for development of a DSA. They are input that the DSA preparers utilize to present a hazard evaluation supporting and justifying the final TSR control set and identifying those DBAs or EBAs that warrant further evaluation in the accident analysis, as discussed in Section 3.1 Accident Type Selection.

[8] The Appendix A format is consistent with Appendix G to DOE-STD-1189-2008.

Equally important, all key assumptions in hazard scenarios need to be identified and justified. A list of all assumptions, and the controls selected to protect these assumptions as described in Chapter 8, are normally included in the hazard evaluation table. For example, the unmitigated frequency for a gas cylinder missile hazard may be *Unlikely* due to its relatively infrequent presence for maintenance activities. Such considerations are not necessarily associated with an administrative control, but assumptions and their bases should be explicitly identified. Other examples include key assumptions regarding the MAR, type and amount of explosives present in TNT (Tri-Nitro-Toluene) equivalent calculations, and assumptions in support analyses. Controls that protect assumptions are not credited for either frequency or consequence reductions but need to be protected for basic assumptions used in the analysis to remain valid. It is important to note that such defining assumptions will likely warrant some level of Safety SSC designation or administrative control to ensure that the assumptions remain valid in the future. In those cases where unplanned hazards or activities have a real potential of being introduced into the nuclear facility (e.g., due to human error and the hazard exists elsewhere on the DOE site), they may need to be analyzed or their exclusion protected with an initial assumption of the analysis. Chapter 8 provides addition discussion of considering whether key assumptions or initial conditions warrant TSR coverage.

Table 2-11. DSA Hazard Evaluation Table Example.

Event No.	Event Cat.	Event Description	Causes	Unmitigated Analysis			Preventive Features	Mitigative Features	Mitigated Analysiss		
				Freq. Level	Consequence Level	Risk Class			Freq. Level	Consequence Level	Risk Class
S-xx	E-6	Vehicle impact to facility/containers Location: Building xxx Release Mechanism: Impact and spill MAR: 10 kg PE-239 Initial Condition: TRU waste in metal containers	Vehicle accident: Operator error (excessive speed, inattention) Operator illness/incapacitation (e.g., heart attack) Mechanical failure of vehicle Improper maintenance on vehicle	A	Radiological FW – High CW – Moderate MOI – Low Chemical FW – Low CW – Low MOI – Low	 I I III III III III	**SSCs:** Concrete vehicle barriers **Administrative:** Transportation Safety Program (establish speed limits on site roads, training) Vehicle maintenance program	**SSCs:** TRU waste packaging for stored waste (IC) **Administrative:** Emergency Preparedness Program (emergency response activities); Procedures and Training Program (workers trained to evacuate)	U	Radiological FW – Low CW – Low	 III III

Note: Underlined controls are credited in the mitigated analysis to reduce frequency, consequences, and risk class

3 ACCIDENT ANALYSIS OVERVIEW

This chapter provides a high level overview of the accident analysis process. The starting point of the overview are the events that were identified in the hazard evaluation table. These events are selected for further accident analysis. This chapter also addresses the following topics: (1) assumption and initial conditions, (2) beyond DBAs, and (3) software quality assurance.

In general, formal accident analysis is performed for HC-2 facilities. Accident analysis is the formal quantification of a subset of accidents, termed DBAs by DOE-STD-3009. The identification of DBAs results from the hazard evaluation ranking of the complete spectrum of facility accidents. These accidents represent a complete set of bounding conditions. The basic components of accident analysis are accident selection, accident scenario development, source term analysis, and consequence analysis. The process is highly iterative to ensure accident scenarios are adequately developed and bounding, the suite of controls are comprehensive and tailored to reflect accident conditions, and all identified facility hazards are understood and controlled.

3.1 ACCIDENT TYPE SELECTION

As previously noted in Section 2.6, Hazard Evaluation Presentation in DSA, only a small subset of the total hazard scenarios identified are used for accident analysis. The predominant purpose of accident analysis is to develop a comprehensive set of hazard controls to evaluate the need for SC controls to protect the public. However, it may also be used to evaluate the need for SS controls for protection of the public or co-located workers. Determining which hazard scenarios to bring forward is determined by the hazard evaluation results.

DBAs are accidents to be analyzed in a DSA for the design of a new nuclear facility, major modification to an existing facility, or were previously identified in the design of an existing facility.

For existing facilities where DBAs were not identified as part of the design, EBAs can be identified. In either case, the accidents are selected from the following types of events:

- Operational accidents - process deviations such as high temperature and high pressure and initiating events internal to the facility such as fire, explosions, and loss of power;
- Natural events such as earthquakes, floods, tornadoes, and wildfires; and
- Man-made external events such as an aircraft crash, vehicular accident, or gas pipe break.

The term EBA is used simply to recognize the fact that the facility was not “designed” to prevent or mitigate the accident, but rather was “evaluated” to ensure that it could do so with existing systems or added systems/controls.

DBAs/EBAs are derived from the spectrum of hazard scenarios developed in the hazard evaluation. Two types of DBAs/EBAs are defined for further analysis: representative and unique. DBAs/EBAs may also be developed for determining the need for SS controls based on co-located worker consequences or chemical consequences to the MOI, if such consequences are not quantitatively evaluated in the hazard evaluation.

The first screen in the hazard evaluation identifies consequences by population in relative bins of increasing severity. Given that accident analysis is focused on documenting consequences at a distance from the facility, initial screening will discard those scenarios whose higher consequence potential relates to the facility worker alone.

The second screen looks at accident types. It is necessary for DSA documentation purposes to include at least one of each major accident type (e.g., fire, explosion, spill, seismic), unless the scoping calculations for the hazard evaluation demonstrate low consequences that do not have the potential to challenge the offsite Evaluation Guideline. These are called representative scenarios with similar preventive and mitigative control sets that bound the collective scenarios for that type.

The final screen consists of looking at the remaining scenarios within a type to see if any would trigger safety SSC designation at a distance from the facility, but involve a different control set than the representative accident already chosen for that type. These are called unique accidents.

As an aid in evaluating many hazard scenarios identified in the hazard evaluation described in Chapter 2, representative or unique EBAs may be selected based on organization by accident category (operational, natural phenomena, external event), accident type (e.g., fire, explosion, spill, etc.), and size (e.g., small, medium, or large fires). Other means of grouping accidents may also be used, especially for complex facilities that may require a broad suite of hazard controls. Table 3-1 presents a list of general candidate EBAs grouped by type and size. It also provides a description of the characteristics of these accident types.

Table 3-1. General Candidate Scenarios.

Scenario	Issues	Description	Remarks
Large fires (pool)	• Fast/high-heat burning combustibles that can lead to metal drum lid failures and expulsion of some or all of the drum contents. • Non-waste combustible liquid inventories.	Fire involving combustible liquids (confined material fire release + unconfined material fire release)	• Size of fire dependent on largest inventory of non-waste combustible liquids. • Examples of combustible liquid sources include vehicle fuel tanks, fuel tankers, hydraulic sources, solvent containers, sump collection tanks that potentially collect fuels, and oil storage/accumulation. • Pool footprint and container storage arrangement defines number of containers impacted. • Pool fires can cause drum lid loss and expulsion of some or all of the container contents leading to unconfined combustible material releases; not all containers are necessarily ruptured leading to confined material releases for some containers. • Fire mitigation may lead to the spread of the fire into a larger pool due to the potential addition of water. • Can lead to requirements for liquid confinements (dikes, berms, etc.), restrictions on fuel inventories, prohibiting fossil-fueled vehicles, and fire protection systems.
Large fires (high-heat propagating)	• Containers of high heat release combustibles that can lead to propagation of the fire from one metal container to the next. • Waste combustible liquid/metal inventories.	Fire involving combustible liquids/metals (volatile liquid fire release)	• Size of fire dependent on largest inventory of waste combustible liquids/metals. • Examples of combustible liquid/metal sources include flammable liquid storage and alkali metal storage. • Facility inventory and container storage arrangement defines number of containers impacted. • Generally, the entire contents of volatile liquid content containers involved in fire; may involve other containers in a facility as confined material releases if fire is large enough to extend beyond containers with combustible liquids and metals. • Fire mitigation may lead to a larger fire due to the potential addition of water to alkali metals. • Can lead to inventory limits, segregation of these types of containers from other containers, and fire protection systems requirements.

Table 3-1. General Candidate Scenarios.

Scenario	Issues	Description	Remarks
Large fires (lower-heat propagating)	• Combustible containers that can lead to propagation of the fire from one container to the next. • Combustible container inventories.	Fire involving combustible containers (confined material fire release)	• Size of fire dependent on maximum inventory of combustible containers in a facility or area. • Examples of combustible containers include wooden crates and plastic overpacks. • Facility inventory and container storage arrangement defines number of containers impacted for combustible containers inside facility; inventory of combustible containers defines number of containers impacted if outside or segregated. • Generally, fires of this type do not involve metal container lid loss and are modeled as confined material releases. • Can lead to inventory limits, segregation of these types of containers from other containers, and fire protection systems requirements.
Large fires (normal combustibles)	• Normal combustible materials that can lead to fires impacting containers in a facility. • Facility combustible loading.	Fire involving normal combustibles (confined material fire release)	• Size of fire defined by the Fire Hazards Analysis Maximum Possible Fire Loss based on facility combustible loading. • Examples of normal combustibles include wooden pallets, packaging materials, construction materials, and office equipment. • Facility inventory and container storage arrangement may define number of containers impacted. • Generally, fires of this type do not involve metal container lid loss and are modeled as confined material releases. • Can lead to combustible material control program and fire protection system requirements.
Small fires (normal combustibles)	• Fuel packages that can lead to fires that are not large enough to actuate fire suppression systems but can impact containers in a facility. • Unmitigatible fire.	Fire involving normal combustibles (confined material fire release)	• Size of fire defined by maximum fuel package that will not activate the wet-pipe sprinkler systems in a facility. • Relevant issues include height of facility ceilings, set-point of sprinklers, and fuel package. • Combustible load associated with that fire and container storage arrangement defines number of containers impacted. • Generally, fires of this type do not involve metal container lid loss and are modeled as confined material releases. • Can lead to combustible material control program.

Table 3-1. General Candidate Scenarios.

Scenario	Issues	Description	Remarks
Small fires (pyrophorics)	• Pyrophoric radioactive material fire. • In container or glovebox.	Fire involving pyrophoric radioactive materials (metal/chip fire release)	• Size of fire defined by amount of pyrophoric material in container or glovebox. • Examples of pyrophoric radioactive materials include plutonium/uranium metals, chips, and fines. • Generally, only single container or glovebox impacted unless fire propagates to medium fire due to other combustibles. • Fires of this type are modeled as metal or chip fire releases. • Can lead to limitations or restrictions on pyrophoric materials and glovebox inerting.
Medium fires (facility)	• Standard combustible material package that can lead to fires impacting containers in a facility. • Combustible fuel package.	Fire with maximum expected fuel package (confined material fire release + unconfined material fire release)	• Size of fire defined by largest expected combustible fuel package based on facility operations. • Examples of fuel packages include a specific number of wooden pallets, drum liners, and TRU package transporter slip sheets. • Combustible load associated with that fire and container storage arrangement defines number of containers impacted. • Fires of this size could involve normal combustibles or fast burning combustibles like plastics and can cause drum lid loss and expulsion of container contents leading to unconfined combustible material releases; not all containers are necessarily ruptured or fuel package may only involve normal combustibles leading to confined material releases. • Fire propagation in waste container stacks using wooden pallets should be considered. • Can lead to combustible material controls on fuel package size and separation from containers and on fire protection system requirements.
Medium fires (glovebox)	• Combustible materials that can be located in a glovebox line that can lead to fires impacting the glovebox line. • Glovebox combustible loading.	Fire involving glovebox line combustibles (unconfined material fire release + volatile liquid fire release)	• Size of fire defined by largest expected combustible fuel loading in a glovebox line based on facility operations. • Glovebox line inventory may define impact. • Generally, fires of this type do not burn the materials inside of the container and are modeled as unconfined combustible material releases and volatile liquid releases. • Can lead to combustible material controls on glovebox and fire protection system requirements.

Table 3-1. General Candidate Scenarios.

Scenario	Issues	Description	Remarks
Vehicle fires (pool)	• Vehicle fuel tank fires that can lead to metal drum lid failures and expulsion of drum contents. • Vehicle fuel tank inventories.	Fire involving combustible liquids (confined material fire release + unconfined material fire release)	• Size of fire dependent on largest inventory of combustible liquids associated with vehicle fuel tanks. • Pool footprint, vehicle inventory and container storage arrangement defines number of containers impacted. • Pool fires can cause drum lid loss and expulsion of some or all of the container contents leading to unconfined combustible material releases; not all containers are necessarily ruptured leading to confined material releases for some containers. • Can lead to requirements for restrictions on fuel inventories in transport vehicles or prohibiting fossil-fueled vehicles.
Range fires	• Exterior combustible materials that can lead to fires impacting containers in a facility or in an area. • Combustible materials in close proximity to storage areas.	Fire involving normal combustibles (confined material fire release)	• Size of fire defined by the combustible loading in close proximity to a facility or a waste storage area. • Facility/area inventory and container storage arrangement may define number of containers impacted. • Generally, fires of this type do not involve metal container lid loss and are modeled as confined material releases. • Can lead to combustible material control program associated with zones of limited combustibles around facilities or storage areas.
Large spills/fires (aircraft crash, vehicle crash)	• Aircraft or vehicle crashes can lead to ruptured containers and subsequent fires involving uncontained materials. • High energy vehicles.	Aircraft/vehicle crash leading to spill and fire (confined material fire release + unconfined material fire release + confined material spill release)	• Size of spill dependent on energy associated with the crash. • Size of fire dependent on amount of fuel in analyzed aircraft or transport vehicle. • Pool footprint and container storage arrangement defines number of containers impacted; some containers breached by impact energy of the plane. • Pool fires can cause drum lid loss and expulsion of some or all of the container contents leading to unconfined combustible material releases although assuming that all breached containers burn their contents as unconfined materials is generally conservative; assuming that the non-breached containers in the fuel pool are confined material releases may be assumed.

Table 3-1. General Candidate Scenarios.

Scenario	Issues	Description	Remarks
Spills (liquids)	• Containers with contaminated liquids can be breached leading to spills. • Container liquid inventories.	Spill involving liquids (liquid spill release + powder resuspension release)	• Size of spill dependent on the largest inventory container/component with liquids. • Examples include tanks, tankers, piping systems, and storage containers (liquids can include sludges). • Entire contents of container/component involved in spill. • Depending on potential for discovery of the spill, spill may go undetected leading to dry out of liquid and potential resuspension of the radioactive material contents. • Can lead to inventory limits on containers/components with liquids.
Spills (containerized solids)	• Containers with contaminated solids can be breached leading to spills. • Container inventories.	Spill involving containerized solids (confined material spill release)	• Size of spill dependent on the largest inventory container(s) with wastes that are handled as a unit. • Examples include drum(s), box(es), pallet(s) of drums, TRU package transporter assembly, cargo container, and specialty container. • Entire contents of container(s) involved in spill. • Generally modeled as confined material spills. • Can lead to inventory limits on containers/components or on limits to number of containers involved in a lift. • Need to determine if the container is breached by the impact from the spill.
Spills (un-containerized solids)	• Uncontained contaminated solids in glovebox lines can be dropped leading to spills. • Glovebox inventories.	Spill involving un-containerized solids (unconfined material spill release)	• Size of spill dependent on the largest inventory of material in a glovebox line. • Examples include sorted radioactive materials, unpackaged wastes, and hazardous materials. • Generally modeled as unconfined material spills. • Can lead to inventory limits on glovebox lines.
Large spills (containerized solids)	• Containers with contaminated solids can be breached due to loads being dropped upon them leading to spills. • Elevated loads.	Spill involving containerized solids (confined material spill release)	• Size of spill dependent on the size of loads being lifted above waste container storage/staging areas. • Inventory of lift as well as footprint containers are included in the spill. • Entire contents of container(s) involved in spill. • Generally modeled as confined material spills unless the container is breached. • Can lead to limits on the number of containers involved in a lift or on the path taken by lifted materials.

Table 3-1. General Candidate Scenarios.

Scenario	Issues	Description	Remarks
Vehicle spills (containerized solids)	• Transport vehicle loads with containers of contaminated solids can be breached due to vehicle accidents leading to spills. • Transport vehicles.	Spill involving containerized solids (confined material spill release)	• Size of spill dependent on the amount of containers on a vehicle load. • Inventory of transport vehicle defines the number of containers impacted. • Entire contents of container(s) involved in spill. • Generally modeled as confined material spills unless the container is breached • Can lead to limits on the number of containers or inventory on a transport vehicle.
Punctures (containerized solids)	• Containers with contaminated solids can be punctured leading to spills. • Forklift operations. • Gas cylinder missiles.	Spill involving containerized solids (unconfined material spill release)	• Size of spill dependent on the largest inventory container(s) with wastes that can be impacted by forklift tines. • Generally, a fraction of the contents of container(s) punctured involved in the spill, depending on the type of materials in the containers; powder-like wastes can have full involvement; contaminated solid wastes do not “flow” out the puncture hole as readily and only a fraction of the material actually spills. • Generally modeled as unconfined material spills. • Can lead to inventory limits on containers and restrictions on forklifts.
Explosions or Over-pressurization (containers)	• Containers with flammable gas generation can have contents ignited leading to container explosion. • Container flammable gas generation.	Internal container explosion (overpressure/ explosion release)	• Size of release dependent on the largest inventory container with materials that can generate flammable gases and where the container is vulnerable to internal explosions or overpressurizations • Generally, a fraction of the contents of the container involved in the release since material at bottom of container is impacted less than that at the top. • Generally modeled as explosive release on surface contaminated materials. • Can lead to container venting requirements.
Explosions (glovebox)	• Glovebox that accumulates flammable gas can have gas ignited leading to glovebox explosion. • Glovebox flammable gas accumulation.	External explosion in glovebox line (glovebox overpressure/ explosion release)	• Size of release dependent on the largest inventory glovebox with materials that can generate flammable gases or where flammable gas can accumulate. • Examples of gas sources include furnace operations with organics, chemical reactions, propane or natural gas lines, air intakes located near sources of gas, and opening of containers with internal flammable gas. • Entire contents of the glovebox can be involved in the release since material may be exposed to the overpressure/blast effects of the explosion. • May be modeled as explosive release on powders and surface contaminated materials. • Can lead to furnace controls, glovebox ventilation requirements, rupture disks, glovebox inventory limitations, or glovebox material restrictions.

Table 3-1. General Candidate Scenarios.

Scenario	Issues	Description	Remarks
Explosions (facility)	• Flammable gas accumulation or inventories can have gas ignited leading to explosion. • Flammable gas accumulation or storage.	External explosion in facility (confined material spill release)	• Size of explosion based on largest source of flammable gas used in the facility. • Examples of gas sources include propane-fueled vehicles, acetylene gas cylinders, propane or natural gas lines, and air intakes located near sources of gas. • Room or area top-tier inventory defines number of containers impacted. • Some containers potentially impacted by blast wave leading to stack toppling or container breach and confined material spills; top-tier containers potentially impacted by falling debris from the facility ceiling leading to container punctures and confined material spills. • Can lead to flammable gas inventory limitations/restrictions, facility ventilation requirements, or hot work permitting process.
BLEVE (Boiling Liquid Expanding Vapor Explosions) Explosions/ Spills/Fires (facility or area)	• Flammable gas container involved in a fire can result in container overpressure and BLEVE. • Flammable gas containers.	BLEVE in facility or exterior area (confined material spill release + unconfined material fire release)	• Size of BLEVE based on largest flammable gas container in the facility or area. • Examples of gas sources include propane fuel tanks on vehicles, propane storage tanks, propane delivery tankers. • Facility or area inventory and container stacking arrangement defines number of containers impacted. • Some containers potentially impacted by blast wave leading to stack toppling or container breach due to missiles and confined material spills; breached container contents ignited by fireball leading to unconfined combustible material releases. • Can lead to flammable gas inventory limitations/restrictions, routing controls on flammable gas deliveries, or siting criteria for flammable gas tanks.
Explosions/ Fires (glovebox)	• Glovebox accumulates flammable gas. Gas ignited leading to glovebox explosion and fire. • Glovebox flammable gas accumulation.	Explosion and fire in glovebox line (glovebox overpressure / explosion release + unconfined material fire release)	• Size of release dependent on the largest inventory glovebox with materials that can generate flammable gases or where flammable gas can accumulate. • Examples of gas sources include chemical reactions, propane or natural gas lines, air intakes located near sources of gas, and opening of containers with internal flammable gas. • Entire contents of the glovebox involved in the release since material may be exposed to the overpressure/blast effects of the explosion and the subsequent fire. • May be modeled as explosive release on powders and surface contaminated materials along with unconfined combustible material fire releases. • Can lead to glovebox ventilation requirements, rupture disks, glovebox inventory limitations, or glovebox material restrictions.

Table 3-1. General Candidate Scenarios.

Scenario	Issues	Description	Remarks
Explosions/ Fires (facility)	• Flammable gas accumulation or inventories can have gas ignited leading to explosion and fire. • Flammable gas accumulation or storage.	External explosion and fire in facility (confined material spill release + unconfined material fire release)	• Size of explosion and fire based on largest source of flammable gas used in the facility. • Examples of gas sources include propane-fueled vehicles, acetylene gas cylinders, propane or natural gas lines, and air intakes located near sources of gas. • Room or area top-tier inventory defines number of containers impacted. • Some containers potentially impacted by blast wave leading to stack toppling or container breach and confined material spills along with unconfined combustible material fire releases; top-tier containers potentially impacted by falling debris from the facility ceiling leading to container punctures and confined material spills (these materials would not be subsequently ignited since punctures occur at top of containers). • Can lead to flammable gas inventory limitations/restrictions, facility ventilation requirements, or hot work permitting process.
Criticality (container)	• Fissile material in containers arranged and moderated in a manner to cause a criticality • Containerized fissile material	Criticality (criticality release + container overpressure release)	• Size of criticality based on minimum container configuration leading to criticality. • Examples include overmass container stacking, container collapse and breach due to application of loads to containers, and supercompactor crushing with accumulation of densely packed waste. • Configuration defines number of containers involved. • Criticality releases noble gases and volatile fission products; some containers may over pressurize leading to particulate material releases from the containers from the overpressure and container failure. • No mechanism for stopping the criticality other than disruption of the material by mechanical means. • Can lead to container inventory limits and criticality safety program.
Criticality (liquid)	• Liquid fissile material collects in sumps, tanks or glovebox in a manner to cause a criticality • Liquid fissile material	Criticality (criticality release + liquid boiling/ explosive release)	• Size of criticality based on amount of fissile material in liquids. • Examples include glovebox liquid spills and sump collection tanks. • Criticality releases noble gases and volatile fission products; liquid will be violently dispersed due to energy from the criticality leading to boiling or explosive liquid release. • Criticality pulse will disrupt liquid leading to shutdown of the reaction. • Can lead to fissile liquid inventory limits and criticality safety program. • Criticalities involving metals or powders may also need to be evaluated.

Table 3-1. General Candidate Scenarios.

Scenario	Issues	Description	Remarks
NPH Spills (seismic)	• Seismic event results in container toppling and facility collapse leading to spill. • Seismic potential	Spill involving radioactive materials (confined material spill release + liquid spill release + unconfined material spill release)	• Stacks of containers can topple leading to confined material spill releases • Facility structures can collapse leading to debris impacting containers and confined material spill releases. • Tanks of radioactive liquids can breach leading to liquid spill releases. • Glovebox, ducting, and filter plenum inventories can be impacted leading to unconfined material and filter spill releases. • Containers in trenches can be breached from trench collapse leading to confined material spill releases that are mitigated, to some extent, by the earth causing the container failures.
NPH Spills (heavy snow or volcanic ash loading)	• Heavy snow or volcanic ash results in facility collapse leading to spill. • Facility roof strength	Spill involving radioactive materials (confined material spill release + liquid spill release + unconfined material spill release)	• Facility structures can collapse leading to debris impacting containers and confined material spill releases. • Tanks of radioactive liquids can breach due to facility structure impacts leading to liquid spill releases. • Glovebox, ducting, and filter plenum inventories can be impacted by collapsing facility leading to unconfined material and filter spill releases.
NPH Spills (high winds)	• High winds result in facility collapse and wind-borne missiles leading to spill. • Facility wind resistance • High winds affect contained and uncontained material outside of a facility	Spill involving radioactive materials (confined material spill release + liquid spill release + unconfined material spill release)	• Facility structures can collapse leading to debris impacting containers and confined material spill releases. • Exposed containers can be impacted by wind-borne missiles leading to confined material spill releases. • Tanks of radioactive liquids can breach due to facility structure impacts leading to liquid spill releases. • Glovebox, ducting, and filter plenum inventories can be impacted by collapsing facility leading to unconfined material and filter spill releases. • High wind greatly increases radioactive material dispersion and significantly lessens release consequences

Table 3-1. General Candidate Scenarios.

Scenario	Issues	Description	Remarks
NPH Spills/Fires/ Explosion (seismic)	• Seismic event results in container toppling and facility collapse leading to spill and subsequent fires. • Seismic potential	Spill and fire involving radioactive materials (confined material spill release + liquid spill release + unconfined material spill release + confined material fire release + unconfined material fire release)	• Stacks of containers can topple leading to confined material spill releases • Facility structures can collapse leading to debris impacting containers and confined material spill releases. • Tanks of radioactive liquids can breach leading to liquid spill releases. • Glovebox, ducting, and filter plenum inventories can be impacted leading to unconfined material and filter spill releases. • Flammable/combustible liquid or flammable gas containers may be breached, become ignited by damaged electrical equipment, leading to fire. • Fire can impact containerized materials leading to confined material fire releases; fire can impact breached containers and glovebox materials leading to unconfined combustible material fire releases. • Fire can pressurize sealed containers, possibly resulting in a release.

NOTES:
1. All scenarios that apply should be qualitatively analyzed or dispositioned (i.e., some may not be applicable) during the HA.
2. "Large fires" includes "major fires" that could cause collapse of unprotected steel buildings or plugging of HEPA filters resulting in bypass or blow-through.
3. FHA should help develop sizes of fires for maximum expected fuel loadings and plausible failure of combustible control scenarios.
4. Combustible control program can include controls on ignition sources (e.g., hot work, no smoking, etc.).
5. Fire protection system requirements can include fire detection, fire suppression, or fire barriers.
6. HEPA filtration requirements may be derived from any scenario that challenges Evaluation Guidelines or is unmitigated Risk Class I or II.
7. NPH events can also initiate explosions or criticalities, similar to the NPH Spills/Fires discussion, that may need to be evaluated.
8. This list is not necessarily a complete spectrum of accidents due to unique facility or processing hazards.

Another example is provided in Table 3-2, reproduced from Table 3.3-1, Minimum TRU Waste Activity/Hazard Evaluation Event Matrix, of DOE-STD-5506-2007. It correlates 25 hazard scenarios or accidents described in that standard by TRU waste processing activities, for use in the hazard evaluation or as EBAs. The minimum set of events addresses those with the potential for consequences that could be significant enough to warrant crediting preventive or mitigative controls, safety classifications of those controls, and explicit TSRs. Areas of the table marked by "X's" indicate potential applicability. These events are presented according to broad categories that include fires, explosion events, loss of confinement/containment, direct radiation exposure, criticality, externally initiated events, and natural phenomena events. Additional unique events may also need to be evaluated at a particular site.

Table 3-2. Minimum TRU Waste Activity/Hazard Evaluation Event Matrix.

Hazard Evaluation Event [1]	**Character-ization**	**Container Handling**[2]	**Venting &/or Abating/ Purging**	**Staging and Storage**	**Retrieval and Excavation**	**Waste Repack-aging**	**Type B Container Loading/ Unloading**
Fire Events							
Fuel Pool Fire (Event 1)		X		X	X		X
Small Fire (Event 2)	X	X	X	X	X	X	X
Enclosure Fire (Event 3)	X		X			X	
Large Fire (Event 4)	X	X	X	X	X	X	X
Explosion Events							
Ignition of Fumes Results in an Deflagration/Detonation (external to container) (Event 5)		X			X	X	X
Waste Container Deflagration (Event 6)	X	X	X	X	X		
Multiple Waste Container Deflagration (Event 7)	X	X	X	X	X		
Enclosure Deflagration (Event 8)	X		X			X	
Loss of Confinement/Containment							
Vehicle/Equipment Impacts Waste/Waste Containers (Event 9)		X	X	X	X	X	X
Drop/Impact/Spill Due to Improperly Handled Container, etc. (Event 10)		X			X	X	X
Collapse of Stacked Containers (Event 11)		X	X	X			
Waste Container Over-Pressurization (Event 12)	X	X	X	X	X		
Direct Exposure to Radiation Events (Event 13)	X	X	X	X	X	X	X
Criticality Events (Event 14)	X	X	X	X	X	X	
Externally Initiated Events							
Aircraft Impact with Fire (Event 15)	X	X	X	X	X	X	X
External Vehicle Accident (Event 16)	X	X	X	X	X	X	X
External Vehicle Accident with Fire (Combustible or Pool) (Event 17)	X	X	X	X	X	X	X
External Explosion (Event 18)	X	X	X	X	X	X	X
External Fire (Event 19)	X	X	X	X	X	X	X
NPH Initiated Events							
Lightning (Event 20)	X	X	X	X	X	X	X

Table 3-2. Minimum TRU Waste Activity/Hazard Evaluation Event Matrix.

Hazard Evaluation Event [1]	Character-ization	Container Handling[2]	Venting &/or Abating/ Purging	Staging and Storage	Retrieval and Excavation	Waste Repack-aging	Type B Container Loading/ Unloading
High Wind (Event 21)	X	X	X	X	X	X	X
Tornado (Event 22)	X	X	X	X	X	X	X
Snow/Ice/Volcanic Ash Build-up (Event 23)	X	X	X	X	X	X	X
Seismic Event (Impact Only) (Event 24)	X	X	X	X	X	X	X
Seismic Event with Fire (Event 25)	X	X	X	X	X	X	X

[1] Transport activity accidents and control selection are done in compliance with DOE O 460.1B and 461.1.
[2] Movement of TRU waste containers (not including Type B containers) is considered "container handling," even when it is related to the completion of another type of TRU waste activity. When analyzing these events, one must consider the waste being handled as well as other stored/staged waste that may be impacted.

Both examples in Tables 3-1 and 3-2 may be useful for developing hazard scenarios for qualitative evaluation in the hazard evaluation as discussed in Chapter 2.

The process is intended to be straightforward. It does not involve detailed calculations for all potential scenarios. An effective hazard evaluation supports qualitative discrimination. Further requirements and guidance for selecting DBAs/EBAs is provided in DOE-STD-3009-2014 Section 3.2.1, Design/Evaluation Basis Accident Selection, covering representative and unique events.

3.2 ACCIDENT ANALYSIS PROCESS

For those event types requiring an unmitigated accident analysis, the evaluation consists of the following sequence of steps intended to document numerical estimates of dose consequence to the public (or co-located worker as needed for the DSA hazard evaluation).

1. Define the event.
2. Estimate the damage to the facility including SSCs.
3. Identify types and quantities of material involved in the accident.
4. Determine the source term.
5. Determine the radiological dose or chemical consequences.

Chapter 4 addresses steps 1 - 3 for major accident types applicable to DOE nuclear facilities. Chapter 5 addresses step 4 and Chapter 6 addresses step 5 for radiological releases. Chapter 7 addresses step 5 for chemical consequences to the public and co-located worker as needed for the hazard evaluation.

The potential controls identified in the hazard evaluation are further evaluated in the mitigated accident analysis.

3.3 ANALYSIS INPUTS AND ASSUMPTIONS

For most DOE accident analyses, the phenomena being examined have uncertainty. It is typically not possible to derive absolute conclusions from first engineering principles. Therefore, it's important to document the inputs, initial conditions, and assumptions of the accident analysis. DOE-STD-3009-2014 requires that:

> "*Calculations shall be made based on technically-justified input parameters and underlying assumptions such that the overall consequence calculation is conservative. Conservatism is assured by the selection of bounding accident scenarios, the use of a conservative analysis methodology, and the selection of source term and input parameters that are consistent with that methodology.*
>
> *For some input parameters, this section identifies default or bounding values that may be used without further justification. Unless otherwise stated for a particular input value, this section allows use of alternative values when supported by an adequate technical basis. When an input parameter used is not a default or bounding value, an acceptable technical basis of the value describes why the value selected is appropriate for the physical situation being analyzed, and references relevant data, analysis, or technical standards. The completeness and level of detail in the technical basis should increase as the parameters depart from default or bounding values. DOE is developing an Accident Analysis Handbook, which will provide additional discussion on conservative consequence calculations.*"

Both hazard and accident analyses make use of initial conditions (ICs). ICs are specific assumptions regarding a facility and its operations that are used in defining accident scenarios. When not referring to physical facility features, these are sometimes called initial assumptions, however, the use of "IC" in this document refers to either initial conditions or initial assumptions.

As discussed in Sections 3.2.2 and 3.2.3 of the DOE-STD-3009-2014, facilities are analyzed as they exist (or are designed) when quantifying meaningful release mechanisms. For design of new facilities, the unmitigated analysis may need to assume failure of the SSC to determine the potential consequences for safety classifications of SSCs and their appropriate design requirements (e.g., NPH Design Criteria).

Accident scenario description includes, as appropriate, the operating mode of the system, all pertinent aspects of the physical configuration of the system and its environment, and relevant operating parameters (e.g., temperature, pressure, material inventories) at the time the accident is initiated. Where a range of possible initial conditions, physical properties, or environmental conditions exists, the range is specified, and the most conservative physically credible combination of normal operating conditions chosen. An explanation of why the choices are considered conservative is provided. Not all of these assumptions are ICs.

As stated in Section 2.7, Hazard Evaluation Presentation in the DSA, all key assumptions in hazard scenarios need to be identified and justified, and this also applies to the accident analysis. Specific examples of ICs include:

- A vault or building can withstand natural phenomena hazard (NPH) events according to its NPH Design Category;
- Facility geometry or layout affects accident progression or release;
- Solid TRU waste is contained in a certified Department of Transportation (DOT) Type-A drum;
- A certain material is present only within a certified Department of Transportation Type B shipping container;
- Facility and process inventories are limited to those identified; and
- A passive SSC prevents significant consequences.

ICs should not include administrative controls, except those necessary to limit the amount of radioactive or hazardous materials. Controls that protect assumptions are not credited for either frequency or consequence reductions but need to be protected for basic assumptions used in the analysis to remain valid. It is important to note that such defining assumptions will likely warrant some level of Safety SSC designation or administrative control to ensure that the assumptions remain valid in the future. It is important to define and document ICs carefully to ensure they are appropriately controlled, classified as SC or SS and preserved via TSR operating limits, design features or SACs as appropriate.

ICs, other than those that are part of the facility design basis (e.g., Seismic Design Criteria 3 construction) or that will obviously prevent an event (e.g., structure able to withstand vehicle impact), are discouraged from being used since they may skew the unmitigated risk levels and result in unanalyzed or inadequately controlled hazards. For example, a fire door may be credited as an IC for preventing fire propagation. This control may fail (e.g., door is blocked open) so it does not completely prevent the event, but only reduces the likelihood. If the likelihood reduction "moves" the event risk to a level that does not require further analysis, then the adequacy of the control is not evaluated and the safety functions of the door may not be properly determined. Additionally, this may lead to a larger control set since controls identified for other fire events (e.g., combustible material control, fire suppression) may be adequate to protect against this event.

Spreadsheet and computer modeling of accident sequences can provide valuable insights on the sensitivity of parameters, as well as indicating what reasonably lower and upper limits of response might be expected so that an overall conservative consequence is estimated. The foundation of any accident analysis can be reduced to a set of inputs and assumptions. An input can be defined as a value feeding into the analyses that can be measured confidently and is readily obtainable. It could, for instance, be the internal freeboard volume of a tank, the specific gravity of a solution, or the metal skin thickness of a 55-gallon drum. An input value would not be expected to change as more information relative to it is obtained. An assumption, on the other hand, is a value feeding into the analyses that is not known with reliability and accuracy. Significant judgment therefore enters into the process of selecting the value or parameter of interest.

Examples of assumptions would be the rate of dispersion of a flammable gas leaked into a ventilated volume, the degree to which two spilled chemicals that react together might intermingle, or the nature of the physical interactions occurring in a structural collapse. The gas leak example can be calculated, but the means of calculation itself introduces an implicit set of theoretical assumptions and uncertainties. The other two examples intrinsically involve making judgments about what is likely to occur. Analysts should strive to use as few assumptions in analysis as possible, but their presence to some degree is

inevitable. This point is specifically emphasized in *Guidelines for Hazard Evaluation Procedures* (CCPS, 2008):

> *"Because many of the events considered by the team may never have happened before, the team must use their creativity and judgment to decide whether the potential causes and effects of the accident pose a significant risk. The subjective nature of these deliberations may trouble some people who use the results of these studies because this subjectivity creates a lack of confidence in the results. Some people incorrectly believe that if an analyst uses quantitative measures to express the significance of a problem, then the limitation of subjectivity will simply fade away. However, this is not the case."*

Another consideration is that there may be a difference between input parameters used for conservative unmitigated dose consequence calculations and input parameters used to show that the design withstands physical stresses from the accident scenario. For example, dose consequence calculations may use an extremely conservative correlation to calculate aerosol generation for the purpose of classifying controls, however, these assumptions may not be appropriate for the design basis.

3.4 BEYOND DESIGN/EVALUATION BASIS ACCIDENTS

Section 3.5 of DOE-STD-3009-2014 provides guidance on the consideration of the need for analysis of accidents which may be beyond the design basis of the facility. The purpose of an analysis of accidents beyond the design or evaluation basis of the facility is to provide: (1) a perspective of the residual risk associated with the operation of the facility, and (2) additional perspectives for accident mitigation. That standard describes that BDBA/BEBAs need not be analyzed to the same degree of detail as DBA/EBAs. The analysis is intended to provide insight into the magnitude of consequences of such events and to identify potential facility vulnerabilities. The analysis has the potential, therefore, for identifying additional facility features that could prevent or reduce severe accident consequences. Unlike the unmitigated conservative analysis for DBAs/EBAs, a realistic analysis of potential BDBA/BEBA consequences may be performed to determine whether accidents have a much larger consequence (a "cliff edge effect") than the largest DBA/EBA.

After the March 2011 Fukushima Daiichi nuclear plant accident in Japan, DOE embarked upon several initiatives to investigate the safety posture of its nuclear facilities relative to Beyond Design Basis Events (BDBEs). These initiatives included issuing Health, Safety and Security (HSS) Safety Bulletin 2011-01 , "Events Beyond Design Safety Basis Analysis," conducting pilots to refine possible process improvements, and conducting two DOE nuclear safety workshops. DOE issued two reports documenting the results of these initiatives: *Review of Requirements and Capabilities for Analyzing and Responding to BDBEs,* August 2011; and *A Report to the Secretary of Energy: Beyond Design Basis Event Pilot Evaluations, Results and Recommendations for Improvements to Enhance Nuclear Safety at DOE Nuclear Facilities,* January 2013. A summary description of the pilot evaluation process and results is provided in the HSS Operating Experience Level 1 bulletin (DOE HSS OE-1, 2013): "Improving Department of Energy Capabilities for Mitigating Beyond Design Basis Events." Additional details of the pilot activities are provided in a companion technical report, *Technical Details on Beyond Design Basis Event Pilot Evaluations* (DOE Technical Report, 2013).

The focus of the pilot evaluations was the review of BDBEs and response capabilities at four DOE nuclear facilities representing a range of DOE sites, nuclear facility types/activities, and responsible program offices. The pilots looked at: (1) how BDBEs were evaluated and documented in each facility's DSA, (2) potential BDBE vulnerabilities and margins to failure of facility safety features as obtained from general area and specific system walkdowns and design documents reviews, and (3)

preparations made in facility and site emergency management programs to respond to severe accidents. It also evaluated whether draft BDBE guidance on safety analysis and emergency management could be used to improve the analysis of and preparations for mitigating severe accidents (including BDBEs), which were updated and provided as Attachments 1 and 2, respectively, to the DOE HSS OE-1 (2013). The Attachment 2 safety analysis guidance was intended for use in annual updates to DSAs, and is reproduced as follows:

"Attachment 2
Documented Safety Analysis (DSA) Guidance

The purpose of this guide is to provide expectations for performing an enhanced evaluation of beyond design basis events (BDBEs) as a part of the annual DSA updates. It is generally expected that existing DSAs subject to the criteria of Action 2 already include an evaluation of BDBEs as required by DOE-STD-3009. The enhanced evaluation incorporates an analytical approach that was developed during the BDBE pilots, but documents the results of the analysis in the same manner as described in STD-3009. The enhanced evaluation process should incorporate lessons learned as described in, *A Report to the Secretary of Energy: Beyond Design Basis Event Pilot Evaluations, Results and Recommendations for Improvements to Enhance Nuclear Safety at Department ofEnergy Nuclear Facilities*, January 2013.

As with any DSA preparation and update activity, the BDBE evaluation should be conducted by a qualified team leader and a multidisciplinary team consisting of experts in the areas of facility operations, facility safety analysis, structural/mechanical engineering, NPH, and emergency management, the last of which is particularly relevant to the objective of this evaluation. The intent is to perform an expert-based and qualitative evaluation.

The facility 's DSA should serve as a starting point for the evaluation of BDBEs. The DSA is expected to include a discussion ofthe BDBEs considered, and may include a discussion of analyses or enhancements made to the facility to meet DOE Order 420.1 C, *Facility Safety*, requirement to evaluate the impact of changes in NPH data and/or analysis methodologies every ten years. The new analyses and enhancements should identify how the design has "evolved" to provide assurance of safety under events that are beyond the original design basis. As described in the HSS report to the Secretary referenced above, it is prudent for the team to perform a walkdown of the facility to support a qualitative evaluation of how a BDBE may impact the facility (the qualitative evaluation is discussed in the next section of this attachment) and to look for potentially unknown vulnerabilities to BDBEs (e.g., unsealed penetrations or low-lying electrical equipment in the case of flooding accidents). This walkdown also ensures the reviewers are familiar with facility's size, key features and distances to other structures and potential temporary service connections (like fire hydrants or well water sources).

This enhanced BDBE evaluation is intended to identify BDBEs that may cause a release of radioactive material beyond that analyzed in the unmitigated accident analysis in the DSA and/or to disable important controls relied on to mitigate the release of radioactive material shall be evaluated. The types of BDBEs that should be evaluated include:

- Seismic events
- Floods
- Fires
- Lightning
- Wind and tornadoes
- Snow and ice
- Ash fall
- Accidental aircraft crash
- Station blackout, as an initiating event or as a consequence from any of the above events
- Cascading effects of design basis events analyzed in the DSA that were previously ruled out because of the low likelihood of associated multiple failures.

If BDBE's from the above list are excluded, the rationale for exclusion should be documented. The general categories of failures to be considered for each BDBE listed above include:

- Collapse of building structure and interior walls
- Breach of water storage pools or collapse of storage racks
- Loss of electrical power and emergency power equipment (e.g., transformers, switchgear, or motor control centers)
- Loss of electrical distribution systems (e.g., conduit or cable trays)
- Operational failure of active mechanical equipment (e.g., pumps, compressors, or fans)
- Loss of pressure boundary of static equipment (e.g., tanks, vessels, or gloveboxes)
- Failure of distribution systems (e.g., piping, tubing, or ducts)
- Failure of alarms
- Loss of an emergency response center.
- Adverse spatial seismic interaction (e.g., failure of adjacent buildings or failure of adjacent stacks)
- Adverse flood-inducing interaction (e.g., failure of an adjacent water tank)

The enhanced BDBE evaluation should provide a gross estimate of the bounding impacts associated with BDBEs. It is qualitative in that it relies on a simple “what if” type of hazard evaluation technique where a multidiscipline team participates in a brainstorming session to methodically evaluate the potential failures in facility systems, structures, and components (SSCs) that could be caused by each type of BDBE. The evaluation should estimate the consequences associated with failures of SSCs that provide safety functions such as confinement, energy removal (e.g., decay heat removal or fire suppression), or prevention of energetic reaction (e.g., explosion). The evaluation may draw upon existing unmitigated accident analysis performed in the DSA.

This qualitative evaluation process is applied to each type of BDBE so different failure modes and associated effects can be understood. Although a seismic event will typically present the worst-case consequences, it is important to step through all applicable BDBEs using the same structured “what if” brainstorming technique. This information can be important when considering potential mitigation strategies.

SSCs identified as mitigating BDBE consequences should be subjected to a margins assessment (MA) to provide insights into their margin-to-failure. This should be a qualitative assessment based upon expert judgment. Civil/structural engineers should perform the MA by reviewing existing design basis analyses and supporting calculations for SSCs. This information should then be used as a baseline to compare against a SSC's expected response to higher level stresses. A MA can be difficult to accomplish if facility design information is not available, i.e., for older DOE facilities. In this case, the MA may have to rely on bounding, simplified assumptions and judgments by subject matter experts, supported by the results of structured walkdowns. For NPH events, the margins assessment should be accomplished by analyzing the facility for higher stress levels than the systems' design (for example, the next higher seismic performance or design category) based on qualitative expert judgment.

Descriptions of performance capabilities of the existing SSCs should also be added to or referenced in the DSA, as new and relevant information is learned from above BDBE evaluation. SSCs that provide protection against BDBEs, are typically SC controls, or a subset of these controls, credited in the DSA for design basis events. If the BDBE evaluation identifies non-credited SSCs, it is not expected that these SSCs would be classified as SC or SS based solely on BDBE consequences, and, therefore, additional TSRs for these SSCs would not be created. These may include facility features such as temporary utility connections (power or water) and critical parameter instrumentation readings that permit monitoring after a BDBE occurs. The DSA should identify these SSCs as important for providing additional mitigation of BDBEs, and these SSCs should be maintained within the facility configuration management and maintenance programs in the same manner that other non-SC and SS DSA controls are treated to preserve their safety function. PSOs should establish for their facilities whether the Unreviewed Safety Question program should be used to determine the approval authority for changes to BDBE controls, or whether more general provisions of maintenance and configuration control should be relied upon.

> Based on the results of the enhanced BDBE evaluation, existing DSA descriptions of BDBE accident scenarios should be updated as necessary to clarify important assumptions needed to develop abnormal or emergency operating procedures. This may include details such as potential accident conditions associated with the range of BDBEs, cascading effects of certain scenarios, time-frames associated with scenario development, and time-critical mitigative actions. Additionally, emergency management plans for responding to BDBEs (updated using the guidance in Attachment I) could also identify potential facility design changes for consideration. An example would be the addition of standardized connections, outside the facility, that could be used to supply cooling water, deliver fire suppression water, or provide electrical power using resources obtained through emergency management mutual aid agreements. These improvements should also be conveyed as part of the DSA annual update."

Note that the OE-1 Attachment 2 guidance includes BDBA/BEBA evaluation of accidental aircraft crashes. This is not specifically required by DOE-STD-3009-2014, nor the DOE-STD-3009-94 Chg. Notice 3, if less than a likelihood screening threshold. The most recent guidance on BDBA/BEBA evalautions provided in DOE-STD-3009-2014 states:

> *"Operational BDBAs/BEBAs are operational accidents with more severe conditions or equipment failures than are estimated for the corresponding DBA/EBA identified in the unmitigated analysis, or with likelihood of beyond extremely unlikely based on PRA results as described in Section 3.2.1. NPH BDBAs/BEBAs are defined by the initiating likelihood of the natural event itself (i.e., return period greater than the DBA/EBA return period for the next higher level as defined in DOE-STD-1020-2012). Man-made external events determined to be less than 10^{-6}/yr, conservatively calculated, do not require further evaluation in the DSA."*

An inadvertent criticality accident is a subset of operational accidents. DOE-STD-3007-2007, *Guidelines for Preparing Criticality Safety Evaluations at Department of Energy Nonreactor Nuclear Facilities*, Section IV.B provides the following guidance for need for consideration of beyond DBAs:

> *"To satisfy the requirement in 10 CFR 830 Subpart B for consideration of the need for beyond design basis criticality accidents, an acceptable approach is to examine the contingencies that were discussed in the applicable CSEs but were not carried further based on their being not-credible. Collectively, the results may indicate that the overall risk of a criticality accident in a facility needs further evaluation. The purpose of the beyond design basis section is to inform the DOE that there may be accidents that were not considered either collectively or individually in the normal CSE process. An example is that of a very large earthquake that may result in a criticality accident with a larger maximum total number of fissions than expected from a design basis earthquake. The individual CSEs would not address such an event in the normal course of process analysis. If such a review shows that there are good and sufficient bases for not carrying the scenarios forward, then the review can be documented with the conclusion that there is no need for further consideration."*

3.5 SOFTWARE QUALITY ASSURANCE (SQA)

All software related to nuclear safety need to meet DOE SQA requirements in DOE O 414.1D, *Quality Assurance*, and DOE G 414.1-4, *Safety Software Guide for use with 10 CFR 830 Subpart A, Quality Assurance Requirement*[9]. To quote from the draft update to this guide (DOE G 414.1-4A Draft, *Software Quality Assurance Guide for Use with DOE O 414.1D, Quality Assurance*):

> *"When systems depend on software to implement a safety function identified in the DSA, technical safety requirements (TSR), or other formal hazard analysis, that software becomes safety software. It is possible that the software is not explicitly identified in the DSA, TSR or other hazard analysis documents, but the safety function performed by the software would be identified."*

Software developers have the responsibility for ensuring that their software code has undergone appropriate SQA evaluation before it is distributed to the end users. Moreover, the software user has its own responsibility of assuring that the safety software to be used has undergone all elements of the SQA process prior to adopting it for the DSA analysis. As part of the SQA process, software developers should also provide technical manuals and user's guides to assist the analyst in assessing appropriate application domains for the software to ensure proper implementation. The documentation should address system assumptions and their technical bases and describe default parameter values and default computational modes. The methodology for changing these defaults, and documenting such changes, should also be described.

Ultimately, analysts have the responsibility for ensuring that acquired software adequately performs the functions for a given application. The analyst shall determine that the software is not misapplied to circumstances beyond those for which it was designed. Recommendations for organizations that use software codes for safety analysis purposes are:

1. Conduct a thorough evaluation of the software and associated input data.
   - Critically assess the adequacy of software verification and validation activities that have been performed and documented.
   - Review technical manuals and user's guides and assess their adequacy.
   - Identify all generic and site-specific input data and determine appropriateness for proposed applications.
   - Employ a qualified SME to challenge assumptions and default parameter values.

2. Ensure that each potential user has an adequate technical background before being granted access to the code.

3. Train all users.
   - Instruct users on applicable assumptions and default values.
   - Instruct users on who is authorized to change a default value, how a default value is changed, and under what conditions a default value is to be changed.

[9] The guide was written for DOE O 414.1C and is currently being revised to conform to DOE O 414.1D.

4. Verify that modifications perform only the functions for which they were intended and do not perform unintended functions.

Note: If acquired software can be modified, it becomes a custom or configurable software which have different SQA requirements.

5. Conduct acceptance testing before applying the software to an analysis.

6. Ensure configuration control with the site's configuration management program.

7. Ensure that there is a means of reporting any errors that are encountered through the site's Condition Report (CR) program to the software developer.

3.5.1 VERIFICATION AND VALIDATION

The heart of the SQA process is Verification and Validation (V&V). A simplified distinction between Verification and Validation is:

- Verification: The detailed examination of the code to ensure that the coding precisely reproduces the mathematical model approximations in its algorithms.
- Validation: Entails a comparison of the software model results to actual test or physical data.

A more comprehensive definition of Verification and Validation can be found in draft DOE G 414.1-4A. Validation has two components:

1. Scientific assessment.

2. Benchmarking against other models.

Scientific assessment involves examination of encoded algorithms against theoretical principles and data, where available, to assess the ability of those algorithms to accurately model the phenomena of interest. Benchmarking involves comparing the output of one software code with the output of another software code, or the results of a hand calculation or spreadsheet that serves as a baseline. This type of comparison does not necessarily constitute validation, but has merit as part of a validation procedure to the extent the baseline model is generally accepted as a reasonably accurate predictor for the phenomena of interest. Benchmarking exercises can also provide insight into a model's limits of applicability, computing expense, input requirements, and special sensitivities or uncertainties. Ideally, computer code results should be compared against experimental results that were obtained in environments that mimic those to which the model will be applied.

Note: Because of the expense associated with large-scale field tests, this type of data is generally very limited.

3.5.2 SENSITIVITIES AND UNCERTAINTIES

Performing parametric studies can uncover the sensitivity of a model to its various inputs. This can be extremely useful if it can be determined that the model is insensitive to certain parameters, such that validation does not need to overly concern itself with those parameters. Parametric studies can also be useful in situations in which there is a large variability or uncertainty associated with a particular input

parameter. The results can be used in these cases to define parametric specifications that can establish conservative model predictions. The results of any sensitivity analyses should always be fully documented as they are part of the framework that puts specific model results in proper perspective.

3.5.3 MINIMUM REQUIREMENTS FOR APPLICATION

A British working group proposed ten broad applications to modeling analysis in general and reporting of the analysis results in *Atmospheric Dispersion Modeling: Guidelines on the Justification of Choice and Use of Models, and the Communication and Reporting of Results* (Britter, 1995):

1. The documentation should provide a clear statement of the scope and objectives of the analysis.

2. The chosen modeling approach should be described and justified in relation to the analysis objectives.

3. Software used in analyses should be fully documented and include:
   - A description of phenomena addressed and the mathematical representations employed.
   - A description of the structure of the computer code, the encoding of the mathematical representations into algorithms, and the tests the software has undergone.
   - Detailed instructions on how the model is to be used and examples of model runs showing both input data and output results.

4. Sources of data should be specified in detail and justified.

5. Results should be clearly presented (i.e., generous use of graphs, always labeling numerical quantities with appropriate units) and conclusions explicitly stated.

6. Quantitative descriptions should be used when available to avoid ambiguity.

7. Parametric analysis should be performed and documented to demonstrate sensitivity to model inputs and assumptions.

8. Estimates of uncertainty associated with the results should be given and the issue of variability addressed.

9. Only models that have undergone documented verification should be used.

10. The document should give a complete and transparent account of the analysis.

The capabilities of the techniques selected to perform the analysis should also be commensurate with the level of detail required. This capability should be consistent with the "graded approach", which directs (among other criteria) that effort should be proportional to the complexity of the facility and the safety systems relied on to maintain an acceptable level of risk. For a more comprehensive discussion of graded approach, see Section 2.2, Application of the Graded Approach, of DOE-STD-3009-2014. Accordingly, assessment of the possible consequences of an accidental release of radiological or toxic chemical substances into the atmosphere requires computations that could range from creating estimates on a spreadsheet to applying advanced computer phenomenological and transport and diffusion models.

3.5.4 ANS, ASME, AND IEEE STANDARD GUIDANCE FOR COMPUTER MODELS

Several national consensus standards from three Standards Development Organizations (SDOs) provide guidelines on V&V activities for scientific and engineering computer programs for use in the nuclear industry:

- ANSI/ANS-10.7-2013, *Non-Real Time, High Integrity Software for the Nuclear Industry*";
- ANSI/ANS-10.4-1987: *Verification and Validation of Non-Safety-Related Scientific and Engineering Computer Programs for the Nuclear Industry;*
- ASME/NQA-1-2008, *Quality Assurance Requirements for Nuclear Facility Applications, Subpart 2.7*; and,
- IEEE STD-982.1-1998; *IEEE Standard Dictionary of Measures to Produce Reliable Software*.

Programs of this nature are sequenced in two categories:

(1) Those to be performed in parallel with computer model development, or alternatively,

(2) Those performed for existing software.

The process of fully meeting SQA criteria for safety software is discussed in DOE O 414.1D and draft DOE G 414.1-4A. The analyst is encouraged to become familiar with these and the processes contained therein.

4 EVALUATION OF IMPACTS FROM MAJOR ACCIDENT TYPES

4.1 INTRODUCTION

This Chapter describes methods for developing information on the accident progression, and the impact of the accident on hazardous material and SSCs (to support determination of the source term from the facility) for the following accident types:

- Fires (Section 4.2);
- Explosions (Section 4.3);
- Loss of confinement/spills (Section 4.4);
- Chemical reactions (Section 4.5);
- Natural phenomena events (Section 4.6); and
- External events (Section 4.7).

This information will provide the basis for:

- Calculating physical stresses associated with the event that can impact SSCs and hazardous material;
- Establishing the MAR and damage ratio (DR) for the scenario;
- Establishing the ARFs and RFs for the scenario;[10]
- Providing insights to establish a LPF for a mitigated analysis; and
- Aspects of the dispersion analysis (e.g., energy of the release).

This information is also of interest in evaluating the effectiveness of the control set (e.g., ability of fire barriers and sprinklers to mitigate a fire event).

An unmitigated analysis and a mitigated analysis may be performed to support the DSA consequence assessment and control selection, as well as an understanding of the survivability of SSCs and controls during the event. As described in Chapter 2, a mitigated analysis is performed to determine the effectiveness of SS and SC controls. The survivability of the SSCs is a qualitative or quantitative evaluation to determine whether the control can be credited to provide the safety function under the accident conditions, however, their reliability is not part of the hazard or accident analysis because active controls will have specific surveillance requirements to ensure they are operable and available if needed, and passive deisgn features are deemed available based on an assessment that they will survive the accident condition(s).

[10] The convention "ARF/RF" is used throughout this Handbook, which is adopted from the DOE-HDBK-3010-94 that represents the pair of recommended bounding values that are multiplied together to determine the airborne source term, and does not represent dividing the ARF by the RF.

The information developed in these analyses, in conjunction with data and information in DOE-HDBK-3010-94, is used to determine the source term (as described in Chapter 5 of this Handbook).

As stated in Chapter 1, *Introduction*, this Handbook is a technical document containing methodology, data sources, and subject matter references relevant for performing and reviewing hazard, accident, and consequence analyses relevant to DOE nuclear facilities. Regarding the methods, models, and input data presented in this chapter, it should be noted that:

- These models are not all inclusive of the models available;
- Other models may be more appropriate to use for certain conditions;
- Viability of a model should be evaluated by the analyst before using; and
- Use of the model is justified in the accident analysis write-up.

4.1.1 INFORMATION FROM ACCIDENT ANALYSIS TO INCLUDE IN THE DSA

DOE-STD-3009 specifies the format and content of the accident analysis information to be presented in the DSA. Related to the evaluation of the impacts of accident, it is appropriate to include the following information in Section 3.4.3 of the DSA:

- For each operational DBA/EBA, a description of the unmitigated and mitigated scenarios, sufficiently documented to reveal the thought process used for the analysis. This will include a description of the initiating event and progression of the accident. The summary should include the magnitude of the energy release (e.g., size of fire, explosive magnitude) and describe the physical conditions (such as temperature or pressures) relevant to accident progression and impacts on MAR and SSCs. Section 4.2 through 4.4 of this chapter addresses development of this type of information for fires, explosions, and spills.
- For NPH DBA or EBA, a description of (and the results from) the unmitigated consequence assessment utilized to determine the NPH design category. Furthermore, the return period of the resulting design basis NPH event, and the magnitude of the design basis event should be included. Section 4.6 of this chapter addresses development of this type of information for earthquakes, high winds/tornadoes, flooding, heavy snows, lightning, volcanic eruptions, and wildland fires.
- For external-event DBAs and EBAs, this subsection references the analysis of the external event likelihood or presents its technical basis. Section 4.7 of this chapter addresses this type of information for aircraft crashes, external vehicle crashes, and station blackout (total loss of electrical power), however, only provides limited discussions of qualitative and quantitative likelihoods, and instead, focuses on quantitatively evaluating consequences.

For example for fires, the DSA should qualitatively summarize the fire initiator, describe the event progression from fire initiation, to fire growth (including flashover if possible) through extinguishment without external intervention (e.g., fire department response) for the unmitigated analysis, describe expected damages to SSCs, and ultimately define the impacts on the radiological or chemical MAR, including estimates of ARF, RF, and damage ratios. All important assumptions should be identified. Reference should be made to the engineering calculations that include the details of the analysis.

Furthermore for all events (operational, NPH, and external manmade), the impact of the events on SSCs and their ability to function should be included. In such cases, this subsection should reference the analysis or facility documentation, summarize relevant assumptions, and discuss the degree of conservatism in the evaluation. For example, the fire accident summary in the DSA should provide the key inputs and assumptions used in the analysis such as combustible loading assumptions, Fire HA

conclusions on adequacy of fire barriers, physical design features utilized (e.g., liquid berms for a pool fire), etc. Of particular importance are those assumptions that require TSR protection.

4.2 FIRE SCENARIO ANALYSIS

Fire phenomena is of interest in accident analysis due to its ability to contribute to the airborne release of radiological materials directly through entrainment into the buoyant plume or indirectly by converting material into particulate matter through the burning process. Knowledge of the impact of the fire on SSCs and hazardous material will be useful in determining the MAR, DR, ARF/RF, and whether the release may be a lofted plume.

As described in DOE-HDBK-3010-94 a fire:

> *"Generates heat and combustion gases that may destroy/stress the radioactive material and/or the substrate upon which radioactive materials may be deposited, compromise barriers, and/or pressurize containers/enclosure that may lead to the airborne release of contained radioactive materials. Mass flux of vapors from the reacting surfaces suspend material in air. This material is then entrained in general convective currents that provide transport for particulate materials."*

The fire phenomena is also of interest in evaluating the effectiveness of the control set (e.g., ability of fire barriers and sprinklers to mitigate the event) and evaluating the important of fire on safety SSCs such as heat, smoke, and intervention, e.g., water spray, on systems relied upon for facility safety.

Sections 4.2.1 and 4.2.2 describe how a fire event can be defined and analyzed. Details of the analysis are typically documented in a calculation that is then referenced in the DSA.

4.2.1 FIRE EVENT TYPES AND SCENARIOS

Fire Types

Table 4-1 list the types of fires that should be considered for analysis; this list was developed from DOE-STD-5506-2007.

Table 4-1. Fire Types.

EVENT TYPE	DESCRIPTION
Parking Lot Fire	The hypothetical analysis of the facility inventory without qualification of the facility structure or nature of the combustible materials within. This fire is unlimited and unmitigated by any controls and progresses until all hazardous material within a facility is consumed. This fire is used sometimes as a DBA/EBA fire as the consequences bound the potential releases from all other fires discussed in this table. No qualification is made on this fire's magnitude. This fire may also be applied under aircraft crash scenarios in lieu of evaluating the function of various fire barriers and controls post impact.
Fuel Pool Fires	The analysis of liquid fuel fires, separate from other fires, is important because liquid fuel fires have the potential to result in pool fires that have a substantially higher source term than combustible material fires when waste containers are involved in the event.
Small Fires	This type of fire is limited in size and is contained within a fire area.
Enclosure Fire	This type of fire occurs in a specified enclosure such as a glove box or hot cell. Analysis of this type of fire is necessary due to the potential for unique ignition hazards and MAR.
Large Fires	This type of fire represents an event that propagates beyond a single fire area. The configuration of a large fire is dependent on the facility configuration (e.g., a large, multi-level facility may have a room fire, a level fire, and a full-facility fire). The size of the fire analyzed within the DSA will be dependent on assumptions addressed in the FHA (e.g., full facility fire may not be plausible because of non-combustible facility construction/design and lack of operational needs for combustible/flammable materials).

Fire Scenarios

Credible fire scenarios should generally be identified in HA and described in detail in the Fire Hazard Analysis (FHA) (See Section 4.2.2). For all DBA/EBAscenarios it is a good practice to include details that have an effect on the analysis. These details may include room dimensions, contents, and materials of construction; combustible loading; arrangement of rooms in the building; sources of combustion air; position of doors; and numbers, locations, and characteristics of occupants. All assumptions that have a significant effect on the analysis should be listed.

Typically fire scenarios selected for analysis will include those which can result in the release of radioactive material impacting workers or the public. Scenarios that result in similar consequences and controls may be analyzed as a group using the most limiting/severe conditions for that group. For example, the fire types discussed previously can be further categorized as to the location and/or MAR involved in order to develop representative events to address the nature of fire hazards (e.g., with a glovebox, within the facility areas serviced by the confinement ventilation, and external to facilities serviced by the confinement ventilation system).

The scenarios selected should consider:

- The configuration of the fire area and characteristics of the associate fire barriers,
- MAR quantities that could be involved in an accident,
- the presence and type of ignition sources,
- combustible loading, and
- specific hazards that necessitate unique controls to prevent or mitigate a fire accident.

  Note: Materials of construction that are radioactive (considered as MAR) and are involved in the fire, and the chemical form of the radioactive material as different materials with separate chemical forms, may have a different ARF and RF.

Scenarios that are analyzed as a group must be evaluated to ensure that the control set is effective for all scenarios in that group. For example, if a fire suppression system is a control for a group of scenarios, the fire suppressions system needs to be evaluated to ensure that the system will actuate under all the scenarios.

4.2.2 FIRE ANALYSIS

The facilities FHA should serve as the basic input to the DSA fire scenario development and any fire analysis performed to support the DSA. As directed by DOE O 420.1C, the FHA "…must be integrated into safety basis documentation". Integration of the FHA and DSA can be achieved through various approaches with the primary objective of DSA and FHA integration being the consistency of similar fire analyses, credited controls, and conclusions.

In general, the FHA will describe and assess various postulated fires with primary quantitative focus placed on the maximum possible fire loss (MPFL), the maximum credible fire loss (MCFL), and the fire(s) selected as DBA(s) for the DSA. Additional analysis beyond that performed in the FHA may be necessary to serve the purpose of evaluating the impact on hazardous material, structures, and safety SSCs.

It is beneficial to have the assumptions, analytical methods, and conclusions be closely related when these fires are described and analyzed in both the FHA and the fire analysis document supporting the DSA. Execution of the integration between the FHA and DSA has been continually improving in the DOE complex for many years. Detailed discussion of important concepts, approaches, and recommendations has been developed by the EFCOG/SAWG, *Fire Analysis for DOE Nuclear Facilities* (2008) , and in Appendix B, White Paper on Fire Hazards Analysis, in DOE-HDBK-1163-2003.

Appendix B provides example calculation methods that can be used for fire analysis. The Society of Fire Protection Engineers (SFPE) and NFPA also provide numerous publications detailing quantitative fire analysis methodologies.

The level of detail in the fire analyses should be done on a graded approach, depending on the potential consequences of the DBA/EBA fire event. DBA/EBAs that do not challenge established thresholds generally do not require exhaustive analysis and the level of detail as would be expected for DBAs/EBAs that greatly exceed the consequence thresholds of concern. Detail that would be expected for a DBA that exceeds 25 rem to the public should include all the subsections presented here, but fires with less than 25 rem to the collocated worker do not necessarily require this level of detail.

Impact on Hazardous Material

Determining MAR for the Event

One of the key outputs of fire analysis is the determination of the impacted MAR. In addition, the fire analysis provides information used in conjunction with DOE-HDBK-3010-94, determine the DR and ARF/RF of the event.

The amount of material (MAR involved in the event) may be the material within the area impacted by the fire. For example, a small fire within a glovebox that is analyzed to not propagate beyond the enclosure would consider only the material within the glovebox. For large fires all hazardous material in areas potentially impacted by the thermal energy or structural impacts of the fire should be included in the MAR. Therefore, establishing the boundary of the fire's impact area (e.g., firewall, glovebox wall, spatial separation) is important when specifying each MAR.

The determination of a bounding MAR that may be involved in a fire may need to include MAR in adjacent structures. Spatial separation between buildings is evaluated in the FHA and usually evaluated using NFPA 80A (2007), *Recommended Practice for Exterior Fire Exposures*. This will provide information on the type of buildings and distance between the buildings for which a fire in one can result in a fire starting in the adjacent. This can be supplemented by recommendations in FM 1-20 (2007), *Protection Against Exterior Fire Exposure*. NFPA 80A separation values assume that fire department response will be timely. If an unmitigated separation evaluation is necessary, the NFPA 80A separation value is increased by a factor of three.

Determining DR and ARF/RF for the Event

As further discussed in Chapter 5, DOE-HDBK-3010-94 states the following important consideration regarding MAR and DR:

> *"The damage ratio is the fraction of the MAR actually impacted by the accident-generated conditions. A degree of interdependence exists between the definitions of MAR and DR. If it is predetermined that certain types of material would not be affected by a given accident, some analysts will exclude this material from the MAR. DRs of unity (i.e., 1.0) are conservative and do not require justification. If a DR < 1.0 is used, then justification must be provided. Care needs to be taken to ensure DRs are defined in the DSA and applied consistently throughout the analyses."*

The fire analysis should define the scenario progression adequately in order to determine the DR, and the ARF/RF using DOE-HDBK-3010-94. This Handbook provides data on the ARF/RF for the following types of impact on radioactive material:

- Heating of aqueous solution in flowing air without surface rupture of bubbles.
- Boiling (bubbles continuously breaking the surface of the bulk liquid with <30% of the volume of the liquid as bubbles).
- Volatiles (i.e., iodine) under all conditions.
- Quiescent burning, small surface area pools, or small solvent layer over large aqueous layer burning to self-extinguishment.
- Vigorous burning large pools, or solvent layer burning over limited aqueous layer with sufficient turbulence to disrupt bulk of aqueous layer.
- Large, vigorously burning organic fire that burns to complete dryness or burning solvent over aqueous phase burning to complete dryness for both phases (typically requires external heat source).
- Aqueous solution or air-dried salts under gasoline fire on a porous or otherwise absorbing (i.e, cracks, depressions) surface.
- Airborne release of particulates formed by oxidation at elevated temperature, greater than room temperature but less than self-sustained oxidation (ignition).
- Airborne release of particulates formed by self-sustained oxidation.
- Airborne release of particulates during complete oxidation of metal mass.
- Airborne release during free-fall of molten metal drops.
- Plutonium compounds subjected to thermal stress (temperature <1000 oC, natural convection).
- Contaminated combustible materials heated/burned in packages.
- Dispersed Ash Dropped into Airstream or Forced Draft Air.

Selection and development of ARF/RF is further discussed in Section 5.

Justification of a DR(s) for a fire scenario is generally a function of the size of the fire (e.g., small, large) and facility configuration, as well as how the MAR is being defined due to its interdependence with the DR (see above MAR discussion and Section 5.2.2, Damage Ratio (DR)). For example, MAR for a single glovebox operation is normally associated with a 1.0 DR for a fire inside the glovebox, while MAR for a process area could have lower DRs as determined by the fire analysis. Appendix B can be used to derive DRs for fires based on calculations of heat fluxes to targets, sizes of fuel pool fires, etc. For more complicated analyses, the DOE Central Registry Toolbox code, Consolidated Model of Fire and Smoke Transport (CFAST), can be used to model the potential damages from fires and used to determine appropriate DRs, e.g., whether or not room flashover is predicted (see Appendix B). For TRU waste operations, DOE-STD-5506-2007 provides guidance for selection of DRs associated with fire events based upon the type of metal waste container involved and whether a fuel pool fire or an exposure fire.

Generally DRs < 0.01 require extensive justification. Consideration needs to be given to describing scenarios which attempt to use very small DRs (e.g., DR = 5.2×10^{-4}) to ensure that the bounding event is being described. If there is the potential for another scenario with a higher DR to occur, the differences between the scenarios needs to be clearly outlined in the DBA/EBA section.

<u>Thermal Impacts</u>

Another output of the fire analysis is information useful in determining the environmental stressors on SSCs, in particular credited SSCs relied on to mitigate the event.

Failure of structural members can have a major impact on the accident progression; the fire analysis should consider structural members located near design fires. The strength and stiffness of structural steel begins to worsen when heated leading to possible deformation and failure. Structural, reinforced concrete also may begin to degrade when subjected to extreme temperatures. Building codes generally provide prescriptive fire ratings for structural members, however, detailed analytical methods can be used for design of critical structural components and should include heat transfer analysis and consideration of steel properties at elevated temperatures (Buchanan, 2001).

Radiant heating and direct flame impingement can cause the failure of both passive and active mechanical SSCs. Temperature limits of valves, motors, sensors, etc. should be considered in conjunction with radiant heating models when reviewing impacts to SSCs from design fires. A radiant heating model is presented in Appendix B. Although most fire analysis relates to the direct release of hazardous material due to the impact of the fire itself, fire in control systems in adjacent areas could indirectly cause a release of MAR.

A good practice is to calculate the potential thermal impacts of the fire events to determine what SSCs would be available for both the unmitigated and mitigated consequence calculations.

Smoke Damage

The intent of this section is not to look at the effects of smoke on the workers or members of the public. Smoke can damage equipment and render active SSCs inoperable or behave in an unpredictable manner. Sensitive electrical components, such as those associated with safety instrumented systems could be caused to fail due to smoke conductivity or corrosivity. Circuit bridging has been observed in testing of electrical components subjected to heavy smoke environments (NUREG/CR-7123); consideration may need to be given to the failure state of electronics. Longer term degradation effects of smoke (days to months) are also important considerations upon restart following a fire.

Smoke can also impact nuclear ventiliation system HEPA filters causing them to clog. There are two main failure mechanisms for HEPA filter failure; plugging and blowout/media failure. Plugging occurs when the filter media becomes saturated with particles and prevents adequate airflow. Blowout/media failure occurs when holes or other openings in the media occur and allow particulate matter to pass through the HEPA filter. Both of these mechanisms are important, since they both will create unfiltered leakage paths, which contribute to the amount of released material. The effect of HEPA filter failure needs to be included in assessment of radioactive releases in a safety analysis. In the case of plugging, the fire generates hot gases, which pushes smoke and contamination outward in the absence of adequate HEPA filter flows. With HEPA media failure the ventilation system flows are no longer effectively filtered. Filter clogging occurs before blowout/media failure, and therefore, has been used to determine when loss of confinement occurs.

Correlations have been developed by researchers and the fire protection industry and used in FHAs and DSAs to estimate the rate of smoke loadings on HEPA filters, however, there is no one universally-accepted model, nor universally-accepted criteria recommended for determining when plugging causes loss of confinement or filter blow-through. An example of one model is provided in *Analysis of Filter System Soot Loading for Postulated Fires in the K-Area Complex Container Surveillance and Storage Capability Project (U)* (Sprankle, 2007). A good summary of performance of HEPA filters under accident conditions in terms of filter efficiencies and pressure differentials is provided in the Appendix F, Filtration, of NUREG/CR-6410, *Nuclear Fuel Cycle Facility Accident Analysis Handbook*. Regarding smoke modeling and confinement ventilation systems, DOE-HDBK-1169-2003, *Nuclear Air Cleaning*

Handbook, provides discussions in its Section 10.5, Fire Phenomena, and precautions on modeling are provided in its Section 10.4, Enclosure Fire Modeling in Fire Hazards Analysis, reproduced as follows:

> *"Fire models for FHAs range from simple algorithms that predict thermodynamic changes in enclosures to complex programs that can account for heat, mass transfer, and smoke production in multiple enclosures. Many mathematical models have been installed in software codes and are available on the Internet bulletin boards of various government agencies. These codes can predict the development and spread of fire and smoke conditions through multiple rooms, and can account for changes in the structure and composition of enclosures. Application of these models requires considerable understanding of their use and limitations, statements of which are usually included in the instructional text published with the software codes. Reduction of complex models to simple terms supported by empirical data is often useful in predicting uncomplicated systems."*

4.3 EXPLOSION ANALYSIS

Explosions are of interest in accident analysis due to their ability to contribute to the airborne release of radiological materials directly through entrainment into gases expelled from the explosion and/or the pressure wave or by mechanical impact from missiles produced by the explosion (fragmentation). Explosions are also of interest in evaluating the effectiveness of the control set (e.g., barriers to mitigate the event) or of preventative controls to prevent the explosion (e.g., by inhibiting buildup of combustible gases). Other important effects of explosions include environmental challenges to SSCs.

Explosions can be defined in a variety of ways. In general, an explosion is said to have occurred in the atmosphere if energy is released over a sufficiently small time in a sufficiently small volume so as to generate a pressure wave of finite amplitude traveling away from the source. This energy may have originally been stored in the system in a variety of forms; these include, chemical or pressure energy, for example. However the release is not considered to be explosive unless it is rapid enough and concentrated enough to produce a pressure wave that one can hear. Even though many explosions damage their surroundings, it is not necessary that an explosion produce external damage. All that is necessary is that the explosion is capable of being heard (Baker et. al., 1983).

DOE-HDBK-3010-94 describes explosion accidents as follow:

> *"Generate shock and blast effects with potential for gas flow subsequent to the explosive event that may subdivide/deagglomerate and entrain material. Explosive reactions may result from chemical (e.g., oxidations involving branch-chain products, oxidations of gas-oxidant mixtures) or physical (over pressurization to failure of tanks or vessel, vapor explosions) reactions. Shock waves are supersonic pressure waves (pulses) that can transmit an impulse to materials and the surrounding structures resulting in shattering of solid items. Shock waves are a true wave phenomenon and involve little gross motion of propagating medium. The potential for damage from shock waves has been extensively characterized.*
>
> *Blast effects are typically subsonic and involve material entrained in the gas flow. Blast effects are often more damaging. Blast effects are not subject to the same reflection/amplification phenomena as shock waves because they have significant momentum and inertia. The gas expanding from the explosion zone carries material from the explosion site. If the explosion is adjacent to the MARs, then blast effects can cause damage above and beyond the initial impulse loading. Some explosive reactions may be followed by chemical reactions, material vaporization,*

or fires that lead to substantial gas flows following the explosive event. These gas flows may also entrain material. Deflagrations do not involve shock, but can simulate blast effects. Under proper conditions (e.g., confinement, structural features that enhance turbulence), deflagrations can transition to detonations and produce shock waves."

Figure 4-1 is a roadmap of the structured organization for this "Explosion Analysis" subchapter. Basic concepts of the nature of explosions such as types, effects and consequences are recreated followed by the implications that the different explosion scenarios will have on the accident analysis development.

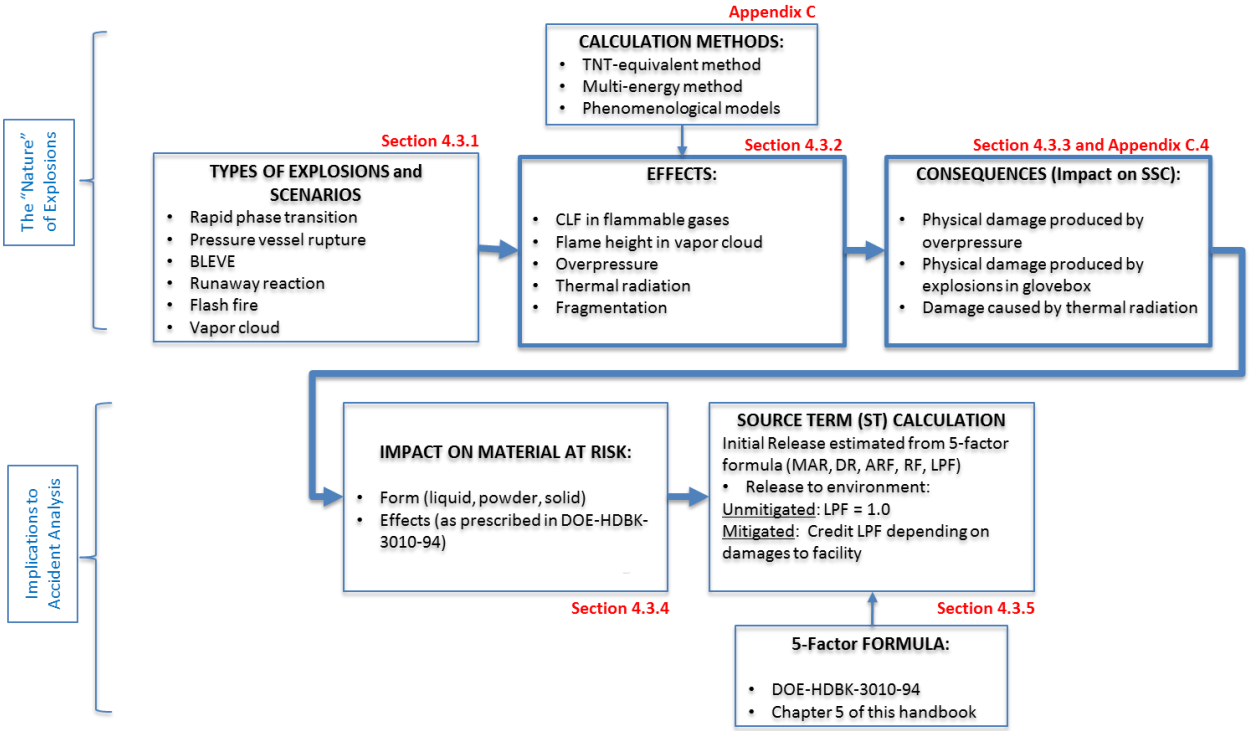

Figure 4-1. Roadmap to Explosion Analysis.

Basic concepts of the types of explosions are introduced in Section 4.3.1, followed by excerpts from the literature that summarizes some of the explosion scenarios.

The effects of explosions are the physical phenomena as a result of an explosion, such as overpressure and thermal radiation. The effects are briefly described in Section 4.3.2 with references on how the analysis can be performed using specified calculations methods from Appendix C. The facilities explosive safety analysis performed in accordance with DOE requirements for control of explosive material will provide some input to this analysis. However, specific analyses may need to be performed by explosive experts to support the DSA to address some of the explosive configuration/situations that may be caused as a result of some unique aspects of some nuclear facilities (such as build-up of hydrogen from radiolysis).

Section 4.3.3 addresses the consequences of explosions in terms of the physical damages that impact important SSCs, such as gloveboxes. Some of the physical damages are described in Section C.4 of Appendix C.

The impact on the MAR is addressed in Section 4.3.4 for the various forms or configurations of radioactive material as well as the explosion effects prescribed in DOE-HDBK-3010-94. The source term (ST) calculation is discussed in detail in Chapter 5 of this Handbook, however, the intention of Section 4.3.5 is to provide the basis for selection of the five factors to calculate the ST initial release from the primary confinement, specifically the ARF/RF for the various explosion effects.

In lieu of performing the detailed analysis of this Chapter, a source term may be developed using an ARF = 1.0 and an RF = 1.0 for comparison to the consequence thresholds in DOE-STD-3009. The TNT-equivalent method in Appendix C may be used in conjunction with an ST = 20% of the TNT-equivalent mass, as described in Section 4.0 (Powders) of DOE-HDBK-3010-94 and as shown on Table 5-1 of Chapter 5.

4.3.1 TYPES OF EXPLOSIONS AND SCENARIOS

4.3.1.1 TYPES OF EXPLOSIONS

Explosions are generally categorized as the result of purely physical phenomena, or as the result of a reaction, most commonly a chemical reaction. Figure 4.3-2 provides a general idea of how explosions are categorized or classified.

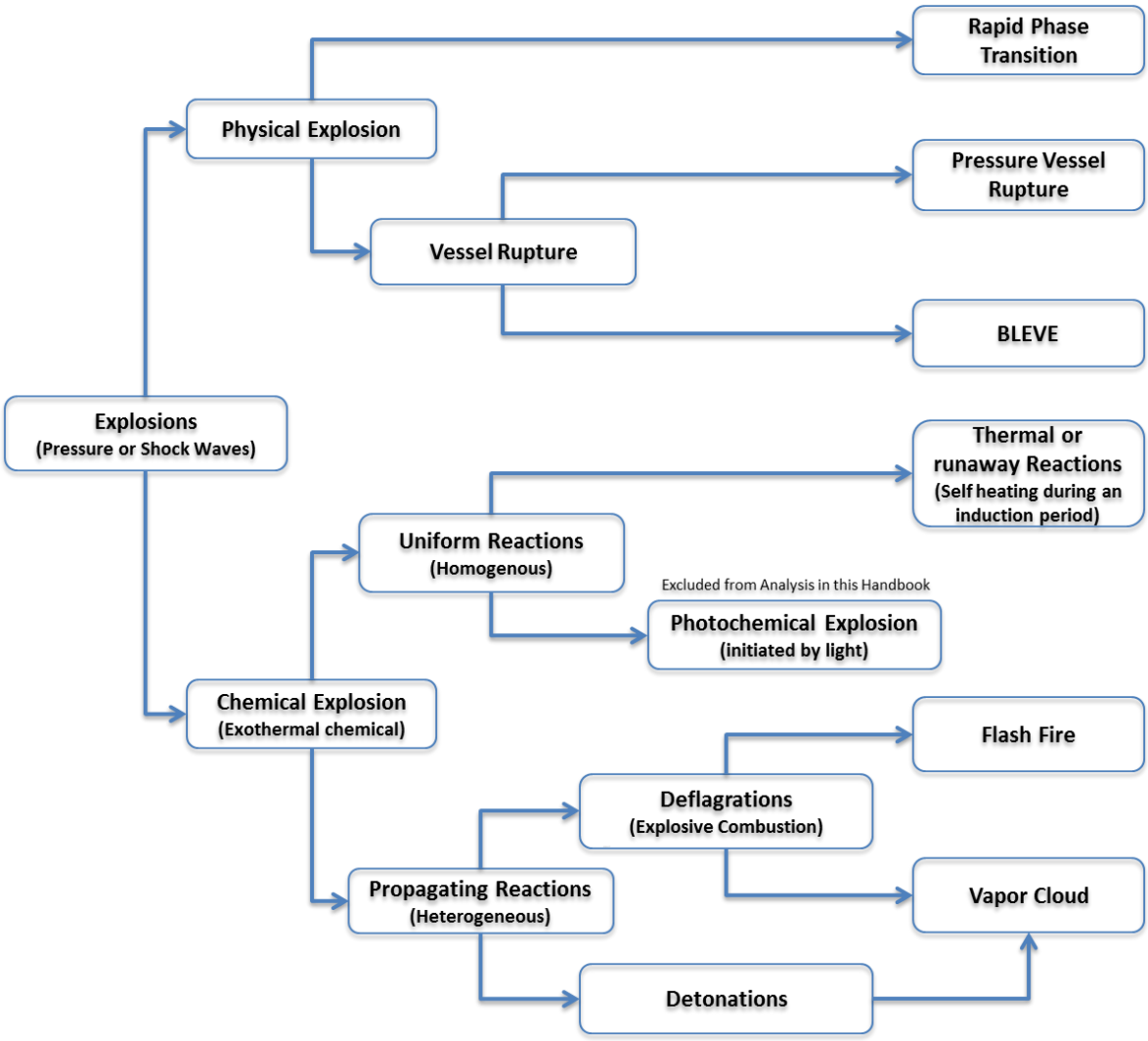

Figure 4-2. Explosion Categorization.

A brief description for each type of explosion is provided in Table 4-2. The DBA/EBA explosion outlined in the facility's DSA may be a single event consisting of any combination of the explosion types in Table 4-2. The DBA/EBA explosion event needs to identify the bounding explosion analyzed and any other explosion phenomena that were considered credible and bounded by the DBA/EBA selection.

Table 4-2. Types of Explosions Descriptions.

EVENT TYPE	DESCRIPTION
PHYSICAL EXPLOSIONS	A physical explosion occurs due to the sudden release of mechanical energy, such as by releasing a compressed gas, and does not involve a chemical reaction. Physical explosions include vessel ruptures, BLEVE and rapid phase transition explosions.
• **Rapid Phase Transition**	**A Rapid Phase Transition** explosion occurs when a material is exposed to a heat source, causing a rapid phase change and resulting change in material volume. (Fig. 4.3-3)
• **Pressure Vessel Rupture**	**A Pressure Vessel Rupture** explosion occurs when a process vessel containing a pressurized material fails suddenly. The failure can be due to a number of mechanisms, including mechanical failure, corrosion, heat exposure, cyclical failure, etc.
• **BLEVE**	**A BLEVE** occurs when a vessel containing a liquefied gas stored above its normal boiling point fails catastrophically. The vessel failure results in sudden flashing of the liquid into vapor, with subsequent damage due to the rapidly expanding vapor, ejection of liquid and vessel contents and fragment impact. A fireball may result if the material is combustible. (Fig. 4.3-4)
CHEMICAL EXPLOSIONS	**Chemical explosions** are those in which pressure is being imposed as the result of a chemical reaction, which could be a combustion reaction, a decomposition reaction, or some other rapid exothermic reaction. This reaction may be either relatively uniform throughout the mass of a material, or initiated at specific point and propagated through the material. Chemical explosions can occur in either the vapor, liquid, or solid phases. Chemical explosions which occur in the liquid or solid phases are sometimes called condensed phase explosions. These are significant due to the high energy density in the materials. The damage from a fire or explosion is due to a number of impact mechanisms. This includes pressure effects, thermal exposure, projectiles and loss of material containment. For explosions, pressure effects are the most common. Any combination of these impacts is possible based on the particulars of the accident. See Section 4.5 of this Handbook for more information on the analysis of chemical reactions.
• **Uniform Reaction**	A **uniform reaction** is a reaction that occurs uniformly through space in a reaction mass, such as a reaction which occurs in a continuous stirred tank reactor. An example of an explosion caused by this type of reaction is the **runaway reaction or thermal runaway**. A runaway reaction occurs when the heat released by the reaction exceeds the heat removal, resulting in a temperature and pressure increase which may be sufficient to rupture the process containment. (Fig. 4.3-5)
• **Propagating reaction**	**A propagating reaction** is a reaction which propagates spatially through the reaction mass, such as the combustion of a flammable vapor in a pipe line, a vapor cloud explosion, or the decomposition of an unstable solid. Propagating reactions are further classified as **detonations** or **deflagrations**, depending on the speed at which the reaction front propagates through the unreacted mass.
• **Deflagrations**	**Deflagrations** are propagating reactions in which energy transfer from

EVENT TYPE	DESCRIPTION
	reacted to unreacted material occurs through ordinary heat and mass transfer mechanisms. The reaction front advances rapidly through unreacted material, but at less than the local speed of sound.
• **Flash Fire**	A **flash fire** results from the ignition of a released flammable cloud in which there is essentially no increase in combustion rate. In fact, the combustion rate in a flash fire does increase slightly compared to the laminar phase. This increase is mainly due to the secondary influences of wind and surface roughness. The principal dangers of a flash fire are radiation and direct flame contact. The size of the flammable cloud determines the area of possible direct flame contact effects. Cloud size, in turn, depends partially on dispersion and release conditions. Radiation effects on a target depend on its distance from flames, flame height, flame emissive power, local atmospheric transmissivity, and cloud size. (CCPS, 2010)
• **Detonations**	**Detonations** are propagating reactions in which energy transfer from reacted to unreacted material occurs via a shock wave traveling at a rate equal to or greater than the local speed of sound. As such, detonations can produce extensive damage over a wide area. For detonations, the reaction front moves equal to or faster than the speed of sound in the unreacted medium.
• **Vapor Cloud**[11]	A **Vapor Cloud** explosion is an explosion resulting from the ignition of a cloud of flammable vapor, gas, or mist in which flame speeds accelerate to sufficiently high velocities to produce significant overpressure (CCPS, 2010). (Fig. 4.3-6)

4.3.1.2 EXPLOSION SCENARIOS

Figures 4-3 through 4-6 illustrates the scenarios of various types of explosions. Explanatory excerpts from *Understanding Explosions* (CCPS, 2003) are provided for these types of explosions. These scenarios also refer to some of the explosions effects, which are discussed later in Section 4.3.2. These scenarios need to be considered, where appropriate, in the hazard evaluation study. The boundaries of each scenario, and the associated MAR need to be clearly defined for each scenario in the hazard evaluation so that the accident analysis can group the events into similar types of explosions in order to determine the appropriate control sets.

[11] The difference between a blast effect and a flash fire is given by the presence of the following conditions:

1. partial confinement and/or obstruction
2. jet release
3. explosively dispersed cloud
4. High-energy ignition source.

If the above conditions are not present, then a flash fire is said to occur.

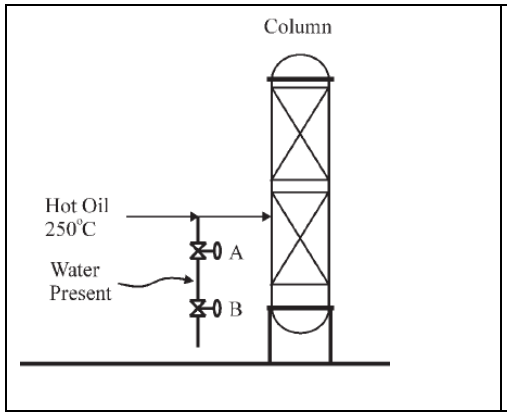

Figure 4-3. A Rapid Phase Transition.

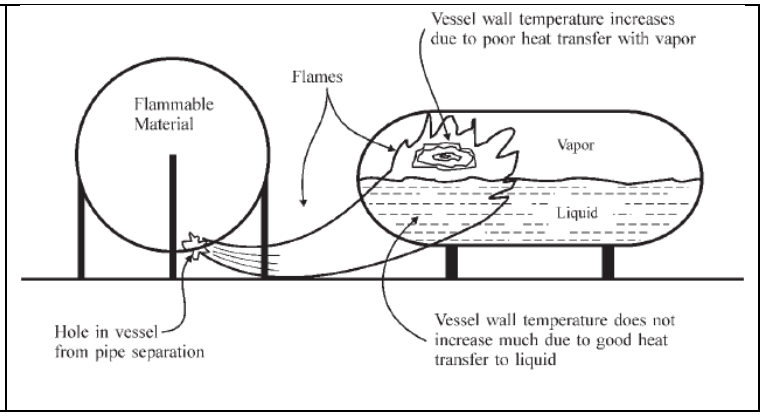

Figure 4-4. BLEVE.

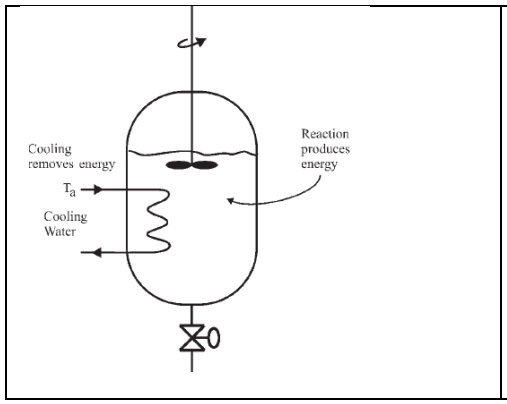

Figure 4-5. Runaway reaction or thermal runaway.

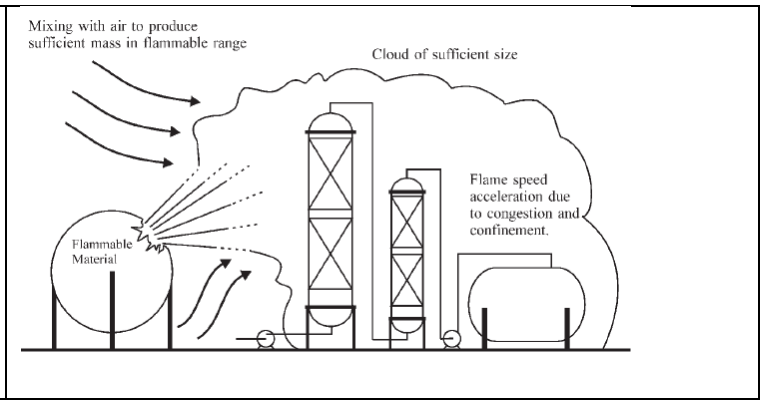

Figure 4-6. Vapor Cloud.

Rapid Phase Transition

If the phase change is from liquid to gas, or from solid to gas (sublimation), the volume of the material will increase hundreds or thousands of times, frequently resulting in an explosion.

Key factors in rapid phase transition explosions include a large temperature difference, a boiling point for the material changing phase that is much lower than the temperature of the heat source, a large difference in heat capacity and a large area of contact between the material and the heat source.

An example of how this can occur is depicted in Figure 4-3:

> A hot oil at a temperature of 250°C was pumped into a distillation column for processing. Initially, valves A and B were closed. Due to a previous maintenance operation, water was present in the blocked-off pipe Section between valves A and B. Valve A was accidently opened during the operation, exposing the water to the high temperature oil. The water flashed explosively, resulting in extensive internal damage to the column.

BLEVE

The rapid depressurization during vessel failure results in sudden flashing of part of the liquid into vapor. The damage is caused, in part, by the pressure wave from the rapid flashing of the liquid and expansion of the vapor. Projectile damage from the container pieces and impingement damage from ejected liquids and solids is also possible. Vessel failure can result from causes such as:

- an external fire;
- mechanical impact;
- corrosion;
- excessive internal pressure; and
- metallurgical failure.

Figure 4-4 shows a vessel exposed to an external fire. The vessel walls below the liquid level are protected by heat transfer from the wall to the liquid, keeping the wall temperature low and maintaining the wall strength and structural integrity.

However, the vessel walls above the liquid level are not protected due to poor heat transfer between the metal wall and the vapor, resulting in an increase in wall temperature and eventual structural failure due to loss of metal strength. The failure may occur at a vessel pressure well below the rated pressure of the vessel or the set pressure of the relief system. After the vessel fails, the liquid flashes almost instantaneously into vapor, resulting in a pressure wave and a vapor cloud. If the liquid is flammable and is ignited, a large fire ball will form. The damage effects for this case include the overpressure from the vessel failure, thermal radiation and possible flame impingement from the fire ball. BLEVEs can occur with vessels containing noncombustible liquids such as water. The damage effects for this case are due to the overpressure from the vessel failure, fragments from the vessel and impingement of the escaping hot water.

Films of actual BLEVE incidents involving flammable liquids clearly show several stages of BLEVE fireball development and growth. At the beginning of the incident, a fire ball is formed quickly due to the rapid ejection of flammable material upon depressurization. This is followed by a much slower rise of the fire ball due to buoyancy of the heated gases. A significant part of the damage from these types of BLEVEs is due to thermal radiation from the large, rising fire ball, which can reach 100 m or more in diameter, rise several hundred meters in height, and last as long as 30 seconds. Blast or pressure effects from BLEVEs are generally limited to the near field. Projectiles from the exploding vessel can be a significant hazard and can result in damage or involvement of adjacent units.

BLEVEs can happen quite quickly, with vessel failure occur ring as soon as five minutes after initial fire exposure. In some instances BLEVEs have been quite delayed, with failure being many hours and sometimes days after initial fire exposure.

Additional information on BLEVEs is provided elsewhere (CCPS, 2010; Lees, 1996).

Runaway Reaction

Figure 4-5 shows a batch reactor system. An exothermic reaction occurs within the reactor. Runaway reactions are possible whenever an exothermic reaction is encountered. This can occur within a reactor, storage vessel or even an open pool or container.

The reaction temperature is controlled by the cooling water flow through the coils. The contents are well stirred, meaning that the temperature and species concentrations are uniform within the reactor. This is classified as a uniform reaction.

However, at some point the cooling water flow is lost. Since the reaction is exothermic, the loss of cooling will result in a higher temperature in the reactor. The higher temperature will increase the reaction rate resulting in a higher rate of heat generation. The result is a runaway reaction, where the reactor temperature increases exponentially. For very reactive chemicals, such as acrolein, hydroxylamine, and ethylene oxide, the temperature can increase several hundred degrees Celsius per minute.

The high temperature causes increased pressure within the reactor due to an increase in the vapor pressure of the liquid and/or generation of non-condensable gaseous products. It is also possible that the high temperatures could result in an additional decomposition reaction. The "decomp" might be more exothermic than the original, desired reaction. In either case, the pressure can rapidly exceed the burst pressure of the vessel, and result in an explosion.

The causes for runaway reactions are mainly:

- loss of temperature control, including inadequate cooling or excessive heating;
- incorrect charging (wrong, too much, or too little material);
- reaction chemistry (unknown exothermic behavior, or unknown decomposition at a higher temperature);
- contamination of reactants or vessel;
- incorrect agitation (too little, too much, failed, or delayed); or
- incorrect batch control (incorrect sequencing of operations).

After a runaway reaction is initiated the high pressure and bursting of the reactor might occur within minutes, or it might take hours, depending on the particular reactive system, heat transfer, etc. With everything else being equal, larger reaction vessels will run away faster than smaller vessels since the surface to volume ratio is smaller and heat losses to the surroundings are less.

An example of a particular type of runaway is the "sleeping reaction."

> This occurs in semi-batch reactors and has resulted in a number of explosions in the chemical industry. The problem is caused by a low reactor temperature while a reactant is being added. The low temperature causes a lower reaction rate, resulting in an accumulation of reactant in the reactor vessel. The reactant concentration will increase beyond the normal concentration expected during addition. If the reactor temperature is then increased, a runaway may occur if the heat generation rate from the reaction exceeds the capacity of the heat removal system.

Another example is a runaway reaction caused by inadequate mixing.

> Suppose two liquid materials with differing densities and miscibilities are reacted in a semi-batch reactor. The first material is added to the reactor and then the second material is added slowly to control the reaction energy generation. However, due to an operator error, the mixer is not started prior to the addition of the second material. This results in a stratification of the liquids in the reactor vessel, with one liquid layer on top of the other. If the mixer is started after appreciable

material has been added, a runaway and explosion can occur. Even if the agitation is not started, the reaction at the liquid interface may cause the phases to mix suddenly leading to a runaway.

Vapor Cloud

A vapor cloud explosion, or VCE, occurs when a large quantity of flammable vapor or gas is released, mixes with air and is subsequently ignited. The vapor or gas fuel is usually released due to the loss of process containment. This could include the failure of a pipe, storage vessel or a process reactor. The rapid discharge of flammable process material through a relief system may also result in a VCE. The vapor may also originate from liquid stored under pressure to maintain it in the liquid state—the discharged liquid will flash rapidly into vapor at ambient pressure. The resulting explosion produces an overpressure which propagates outward from the explosion site as a blast wave. Significant damage from the resulting fire ball is also possible due to thermal radiation.

Several conditions must generally be present for a VCE to result in damaging overpressure.

- The released material must be flammable;
- A cloud of sufficient size must form prior to ignition. If the cloud is too small, or is ignited early in the release, only a small fire ball will result without significant overpressures. A jet or pool fire may subsequently form;
- The vapor cloud must mix with air to produce a sufficient mass in the flammable range of the material released. Without sufficient air mixing, a diffusion controlled fire ball may result without significant overpressures developing; and
- The speed of the flame propagation must accelerate as the vapor cloud burns. Without this acceleration, only a flash fire will result, which may produce significant damage due to thermal radiation and direct flame impingement.

To complicate matters, the above quantities are related to each other. For example, the method and quantity of release will affect the degree of mixing with air and the size of the cloud. These interrelated qualitative features make the characterization of vapor cloud explosions very difficult.

Flame acceleration is an important part of the vapor cloud explosion. The flame accelerates when turbulence stretches and tears the flame front increasing its surface area. The primary turbulence sources are flow turbulence established in the unburned gas as it flows ahead of the flame front, pushed by the expanding combustion products behind it; and turbulence caused by the interactions of the gas with obstacles it encounters. In either case the turbulence results from the motion of the gas. As the turbulence increases, stretching the flame front, the rate at which the fuel is combusted increases because the area of the stretched and torn flame front has increased. As the rate of combustion increases the push on the unburned gases increases, causing them to move even faster, increasing the turbulence further.

This creates a feedback mechanism that accelerates the flame speed. Turbulence from the release could be a contributing factor near the point of release, but flame front acceleration to damaging overpressures can occur even in initially quiescent gas in a congested or confined process area. A congested process area, populated with pipes, pumps, valves, vessels, and other process equipment is adequate to result in significant flame speed acceleration.

Most VCEs result in deflagrations—detonations are unlikely. Increasing levels of confinement and congestion increase the explosion overpressure. While vapor cloud detonations are rare, the higher overpressures can approach the severity of detonations. There is the potential for some VCEs to undergo

a Deflagration to Detonation Transition (DDT), but these scenarios are highly dependent of the geometry of the confinement. If a VCE is confined, the accident analysis should state whether or not a DDT is possible for the VCE of concern.

At flammable concentrations the cloud is typically dense. The dense gas problem is three dimensional, requiring numerical or analytical integration of the concentration profiles within the cloud. It is also not clear what concentration to use for the extent of cloud combustion. The dispersion models do not account for variations in instantaneous cloud concentrations which may result in non-uniform burning of the vapor cloud. Furthermore, there is some evidence that a fuel–air mixture will burn beyond the flammability limits by overdriving it with an energetic ignition source. As a result of these difficulties, some risk analysts use a conservative concentration limit to define the combustible cloud equal to one-half of the Lower Flammability Limit (LFL) (CCPS, 1999a; CCPS, 2000).

Additional information on VCEs is provided elsewhere (CCPS, 2010; CCPS, 1999b; Lees, 1996).

Flash Fire

A flash fire is the nonexplosive combustion of a vapor cloud resulting from a release of flammable or combustible material into the open air. Premixing with air of some part of the vapor cloud is required for a flash fire. A flash fire is non explosive since the flame speed has not accelerated sufficiently to produce damaging overpressures. Flash fires do not create a blast; however, a delayed ignition of a flammable vapor which has accumulated in a congested area, such as a process plant, may result in a vapor cloud explosion.

Flash combustion of a vapor cloud normally lasts no more than a few seconds. Therefore, the total intercepted radiation by an object near a flash fire is substantially lower than in the case of a pool fire. Flash fires are often encountered with metal powders that are pyrophoric. When a flash fire is confined, there is a potential for a dust explosion. Dust explosions create similar considerations to those discussed for VCEs.

4.3.2 EFFECTS OF EXPLOSIONS

Previously, in Section 4.3.1.2, excerpts from existing literature were recreated to provide a general idea of how a specific explosion scenario develops. The effects generated during those explosion scenarios are discussed in this Section. The explosion analysis includes calculations of several phenomena associated with the effects of explosions such as:

- gas generation and flammable gas explosions (Composite Lower Flammability Limit (CLFL) calculation in flammable gases));
- flame height in vapor cloud;
- overpressure (blast effect);
- thermal radiation; and
- fragmentation.

Preventive and mitigative control suites are the primary concern from the results of the various calculation. The calculations are performed using one of the methods developed in Appendix C. A brief description is provide as follow:

4.3.2.1 GAS GENERATION AND FLAMMABLE GAS EXPLOSIONS

An important aspect of defining the event will include analysis of flammable/combustible gas generation. In the DOE Complex, examples of combustible gases include hydrogen, ammonia and many types of volatile organic compounds, such as benzene. In waste tanks, vessels and other containments with enclosed free volume, a combustible gas can burn between its LFL and the Upper Flammability Limit (UFL). Section C.1 of Appendix C provides a standard method to calculate the CLFL when more than one flammable gas is involved in the volatile mixture, often found in radioactive waste drums.

4.3.2.2 FLAME HEIGHT IN VAPOR CLOUD EXPLOSION

Explosion accidents related to the Vapor Cloud formation subjected to specific conditions, will include the calculation of the flame height H when a vapor cloud detonates or deflagrates. In the DOE Complex, examples of vapor cloud explosion involve the release of different gaseous mix into the environment that given the time factor, could envelope the MAR in the proximity. Section C.3.1 of Appendix C provides a basic approach for performing this calculation. Fragmentation from vessels is not considered since it does not involve catastrophic functional failures of receptacles (vessels, containers, jugs) containing the gas, vapor or mix.

4.3.2.3 OVERPRESSURE (BLAST EFFECT)

Overpressure, burst, blast or simply shock effect is one of the many explosion effects that for accident analysis receive greatest attention in the DOE Complex. Blast calculation assesses the sudden release of gaseous mix into the surrounding after a functional vessel rupture (argon, nitrogen tanks). The goal is to calculate the expansion energy, shock wave, or shock effect. Section C.3.2 of Appendix C suggests a method that the analysts can apply to calculate the expansion energy from vessels containing gases or vapor. Thermal and fragmentation effect from the vessel burst could also be calculated with particular emphasis if the MAR is present within nearby locations.

4.3.2.4 THERMAL RADIATION

Thermal effects from explosions when the mix is combustible are of outmost importance to perform for the accident analysis in addition to the overpressure effects. For calculation related to BLEVES, the analysis expands to the calculation of damage distances from the heat flux and the thermal radiation of the vaporized mass that could result in a fireball if the liquid in the failure vessel is combustible. In the DOE Complex, an example of a BLEVE is a failure of a tank due to corrosion containing ammonia. Section C.3.4 of Appendix C suggests simplified formulas to assess the diameter, duration, distance, heat flux of a fireball from a BLEVE.

4.3.2.5 FRAGMENTATION

All the explosion calculations that involve sudden vessel failures such as Pressure Vessel Ruptures, or a BLEVE invokes the fragment release calculation. The nature of this calculation is to assess either analytically or statistically, the distance, velocity, and energy of “a” fragment that could impact the MAR. Section C.3.3 of Appendix C provides suggested methods to approach the fragmentation calculation using both analytical and statistical analysis. DDTs and dust explosions are types of events that should describe the potential for fragmentation during development of the DBA/EBA.

4.3.2.6 CALCULATION METHODS

Along with specific values (CLFL, flame height, energies, heat flux, fragment kinetic energy, etc.) calculated for the accident analysis based on one of the methods described in Appendix C; there are important and common methods used for characterization and explosion assessment, in particular, when the mechanics of overpressure generation are vague and uncertain. These calculation methods are described in Section C.2 of Appendix C and refers to:

- TNT-Equivalent method;
- multi-energy method; and
- phenomenological models.

4.3.3 CONSEQUENCES OF EXPLOSIONS (IMPACT ON SSC)

The consequences that are of interest are:

- damage to structures and/or people caused by blast effects;
- damage from heat effects caused by thermal radiation; and
- damage from missiles generated in the explosion.

Extensive experiments were conducted and recorded in the literature to estimate the consequential damages from explosions. When performing simple bounding calculations, it is usually adequate to compare the calculation results with tabulated withstand values to reach a conservative conclusion over the specific accident scenario that is analyzed.

It is impossible to list in here all the SSCs in the DOE environment that could be exposed to the explosion effects during a specific accident scenario, nevertheless Section C.4 “Consequences of Explosions” lists limit values and their effect on people, structures and a few components, as consequences of blasts and thermal radiation/dose.

4.3.4 IMPACTS ON MATERIAL AT RISK (MAR)

Extensive studies that relates the effects of explosions on the various MAR configuration are referenced in DOE-HDBK-3010-94, which prescribes the following forms of the MAR exposed to the explosion effects:

- liquids
  - aqueous solutions
- solids
  - metals
  - nonmetallic or composite solids
  - powders
- surface contamination
  - contaminated, combustible solids
  - solid, noncombustible unyielding surface
  - HEPA filters – venting of pressurized gases through filters

Three explosion effects prescribed in DOE-HDBK-3010-94 are: shock, blast effects and venting of pressurized liquids and gases. These effects are a broad categorization of those listed in Section 4.3.2 and mainly associated with chemical explosions, but are sufficient to select comparable scenarios for the explosion analysis.

- shock effects:
  - for detonations in or immediately contiguous to a pool of liquid (a bounding respirable release is assessed to be the mass of inert material equal to the calculated TNT equivalent).
  - for detonations in or contiguous to solid metal
- blast effect:
  - for detonations and deflagration at a distance where the pressure impulse is essentially equal to a flow parallel to the surface of the liquid.
  - airborne release from explosive dispersal of molten uranium.
  - accelerated airflow parallel to surface.
  - this condition is representative of powders shielded from the effects of a detonation or strong deflagration by standard containers such as a glovebox or can that are damaged or open.
- venting of pressurized liquids, gases over contaminated, combustible waste.

4.3.5 SOURCE TERM (ST) CALCULATION

This Section addresses the selection of bounding values used in the calculation of the ST. Further discussion of the ST is in Chapter 5 of this Handbook. The intention is to provide the basis for selection of the five factors to calculate the ST initial release from the primary confinement, specifically the ARFs and RFs given the various types of explosions.

The following Table 4.3-2 summarizes the ARF/RF values from DOE-HDBK-3010-94 based on the MAR form and the explosions effects as described in Section 4.3.4 “Impact on MAR” above.

Table 4-3. DOE-HDBK-3010-94 Summary of Recommended ARF, RF Bounding Values.

Physical Form of the Material Affected		Shock Effects	Blast Effects	Venting
3.0 LIQUIDS				
3.2 Aqueous Solutions		For detonations in or immediately contiguous to a pool of liquid, a bounding respirable release is assessed to be the mass of inert material equal to the calculated TNT equivalent. At low mass ratios, the respirable release is comparable to the total material release. As mass ratios increase, the respirable fraction becomes significantly less than the total amount of material released, which decreases with increasing mass ratio as well.	For detonations and deflagration at a distance where the pressure impulse is essentially equal to a flow parallel to the surface of the liquid, an **ARF = 4E-3/hour** (1E-6/second) for the time the pressure pulse is over the liquid and an **RF = 1.0** are conservatively assumed.	n/a
	Venting Below the Liquid Level. Depressurization of liquid via a failure under the liquid surface level. Liquids covered are those at or below their boiling points.	n/a	n/a	**ARF=1E-4 / RF=1.0**
	Venting above liquid level. Depressurization of containment via a failure above the liquid level or overall containment failure.	n/a	n/a	Low Pressure (0.35 MPag or less) Bounding (all solutions): **ARF=5E-5 / RF=0.8** High Pressure (> 0.35 MPag) Median (aqueous solution, density ~ 1 g/cm^3): **ARF=3E-4 / RF=0.9** Median (conc. heavy metal solution, density > ~ 1.2 g/cm^3): **ARF=2E-4 / RF=0.3** Bounding (aqueous solution): **ARF=2E-3 / RF=1.0** Bounding (conc. heavy metal solution): **ARF=1E-3 / RF=0.4**
	Venting of superheated liquid (i.e., flashing spray). Depressurization of liquid above boiling point.	n/a	n/a	≤ 50 °C Superheat **Bounding ARF=1E-2 / RF=0.6** 50 to 100 °C Superheat Median **ARF=2E-2 / RF=0.7** Bounding **ARF=1E-1 / RF=0.7** For superheats greater than 100 °C above the boiling point of the liquid, the **ARF = 0.33** (MFg) 0.91 (where MFg is the mole fraction of pressurizing gas/water vapor flashed) with an **RF = 0.3** if the calculated respirable release exceeds the 50 to 100 °C superheat value.

Physical Form of the Material Affected		Shock Effects	Blast Effects	Venting
4.0 SOLIDS				
4.2 Metals Due to the rapid change in size distribution, the maximum mass of inert material airborne in the respirable fraction is for an MR of 1. Therefore, a bounding ARF/RF of inert material equal in mass to the TNT Equivalent for the detonation is assumed.		For detonations in or contiguous to solid metal, a respirable release of a mass of inert material equal to the TNT equivalent is assessed to be bounding. At low mass ratios (mass inert material/mass TNT equivalent), the respirable release is comparable to the total material release. As mass ratios increase, the respirable fraction becomes significantly less than the total amount of material released, which decreases with increasing mass ratio as well	No significant airborne release is postulated	No significant airborne release is postulated
4.3 Nonmetallic or Composite Solids. The use made of the Steindler-Seefelt correlation in this handbook is considered sufficiently conservative that it can be accepted as a bound for aggregate materials. Accordingly, for detonations in or contiguous to aggregate materials, a respirable release of the mass of inert material equal to the calculated TNT equivalent is assessed to be bounding.		The value used for metal is considered adequate for use with aggregates such as concrete as well. For detonations in or contiguous to solid material, a respirable release of the mass of inert material equal to the calculated TNT equivalent is assessed to be bounding.	If aggregate is hurled with considerable velocity to impact, the crush-impact correlation of Subsection 4.3.3 may be used to characterize the response provided an impact velocity can be estimated. If the aggregate is not hurled with significant velocity, no significant airborne release is postulated.	No significant airborne release is postulated.
4.4 Powders		Based upon data for cratering and associated airborne release of soil a respirable release of the mass of inert material equal to 20% of the calculated TNT equivalent is assessed to be bounding for detonations in or contiguous to powder in open air where shock and blast effects will quickly disperse. The mass of the material-of-concern is dependent upon the concentration of the material-of-concern in the powder.	n/a	n/a
	For detonations in confined areas where immediate dissipation of blast effects is not anticipated, blast effects may produce larger releases than shock effects.	n/a	The largest of the blast and shock numbers is used. A large blast release is expected for deflagrations of large volumes (>25% of free confinement volume) of flammable mixtures above powder with high confinement failure pressure (> 0.17 MPag [25 psig]). For these cases, an **ARF=1.0** with an **RF equal to the fraction of the original source powder < 10 µm is selected.**	n/a

Physical Form of the Material Affected		Shock Effects	Blast Effects	Venting
4.0 SOLIDS				
	Accelerated airflow parallel to surface.	n/a	This condition is representative of powders shielded from the effects of a detonation or strong deflagration by standard containers such as a glovebox or can that are damaged or open. It is noted that small sources of confinement such as a can should not be in the immediate proximity of a detonation when using this value. **Bounding ARF 5E-3/RF 0.3**	n/a
	For the **venting** of powders or confinement failure at pressures to 0.17 MPag (~ 25 psig) or less.	n/a	n/a	Large volume deflagrations (> 25% of confinement volume) where confinement, such as a glovebox, fails at or less than 0.17 MPag can also use this value for evaluating explosive phenomena. **Bounding ARF=5E-3 / RF=0.4**
	For the **venting** of powders or confinement failure at pressures in the range of 0.18 to 3.5 MPag (~ 500 psig) or the venting of pressurized gas through the powder.	n/a	n/a	Large volume deflagrations (flammable gas volume > 25% of confinement volume) use the value for large deflagrations given under blast effects. **Median ARF=5E-2 / RF=0.4** **Bounding ARF=1E-1 / RF=0.7**

Physical Form of the Material Affected		Shock Effects	Blast Effects	Venting
5.0 SURFACE CONTAMINATION				
Contaminated, Combustible Solids		Materials can be fragmented by shock effects but much of the material is extremely flexible and particles are unlikely to be dislodged from porous and fibrous surfaces. This phenomena is considered bounded by the values assessed for venting of pressurized gases over material discussed below. Subsequent ignition and burning are likely to provide the most significant overall release.	Bounded by the values assessed for venting of pressurized gases over material discussed below.Again, subsequent ignition and burning of the substrate material may provide the most significant release. **(Bounding ARF 1E-3/RF 1.0)**	n/a
	Venting of Pressurized Gases Over Contaminated, Combustible Waste.	n/a	n/a	Given the flexible nature of this waste, which does not provide a rigid surface for airflow to act upon, the ARF and RF of 1E-3 and 1.0 for shock flexing of substrate material given in subsection 5.3.3.2.2 is considered to bound the phenomena. This value is applicable only to the portion of waste surfaces that are actually exposed. **Bounding ARF=1E-3 / RF=1.0**
Contaminated, Noncombustible Solids		For detonations in or contiguous to unyielding solid material, a respirable release of the mass of inert material equal to the calculated TNT equivalent is assessed to be bounding. At low mass ratios (mass inert material/mass TNT equivalent), the respirable release is comparable to the total material release. As mass ratios increase, the respirable fraction becomes significantly less than the total amount of material released, which decreases with increasing mass ratio as well.	This phenomena is considered bounded by values assessed for venting of pressurized gases over material discussed below	n/a

Physical Form of the Material Affected		Shock Effects	Blast Effects	Venting
5.0 SURFACE CONTAMINATION				
	Venting of Pressurized Gases Over Contaminated, Noncombustible Material.	n/a	n/a	The entrainment of the material is a function of the characteristics of the flow over the particulate material that may be lying on the surface, the particles, and the surface. Some of the flow characteristics are dependent on the initial pressure and the size of the vent. If the solid is characterized only by loose, externally deposited surface contamination, the release is characterized as to whether the overall containment volume in which the contamination exists is pressurized or not. If it is not, then the gases from the venting source are considered bounded by the phenomena of accelerated airflow parallel to the surface of powders (subsection 4.4.2.2.2.). If the volume is pressurized, the phenomena can be considered bounded by venting of pressurized powders (subsection 4.4.2.3). -Accelerated gas flows in area without significant pressurization **Bounding ARF=5E-3 / RF=0.3** -Venting of pressurized volumes Source > 0.17 MPg (25 psig) **Bounding ARF=5E-3 / RF=0.4** Source < 0.17 MPg (25 psig) **Bounding ARF=1E-1 / RF=0.7** These release values would apply only to loose surface contamination on the solid, not the solid as a whole. No bounding ARF and RF can be uniquely identified for eroded or corroded material on the solid surface that no longer adheres tightly to the bulk solid. However, the release of such material is bounded by the release parameters assumed for loose surface contamination.
HEPA Filters		Based on experimentally measured releases of accumulated particles from HEPA filters experiencing localized failure from a momentary high pressure pulse. **Bounding ARF=2E-6 / RF=1.0**	Based on maximum measured release of accumulated particles by passage of high velocity air through filters to filter break pressure. **Bounding ARF=1E-2 / RF=1.0**	Venting of Pressurized Gases Through Filters. Releases bounded by ARF and RF for blast effects. **Bounding ARF=1E-2 / RF=1.0**

4.3.5.1 SOURCE TERM CALCULATION FOR A VAPOR CLOUD EXPLOSION

Determining the MAR

The MAR, quantity, form and location, involved in a vapor cloud explosion is the material exposed to the cloud and/or in the proximity. The MAR form is suggested in DOE-HDBK-3010-94 and presented in Table 4.3-2. Shock and venting (if applicable) effects on MAR are calculated. No fragmentation is considered since the vapor cloud is the result of a gas release over time t.

Determining the DR

The fraction of the MAR impacted by a Vapor Cloud Explosion for all unmitigated scenarios is Damage Ratio (DR) = 1, unless is feasible to apply a standard or technical basis for a different value. Distance, height, radius, impulse, energy, mitigative and/or design control features are taking into accountability to justify the circumstances (or mitigated scenarios) that predetermined that certain types of material and/or quantity, subjected to the physical stresses, would not be affected by the vapor cloud effects.

Determining the ARF/RF

Given the MAR form and the type of effect(s) the material will be impacted based on the explosion, the circumstances, the type of vessel, location, explosive material, abnormal operational conditions. The analyst could select the ARF/RF from the suggested values in Table 4.3-2 above.

Determining the Release Duration

DOE-STD-1189-2008, *Integration of Safety into the Design Process*, states: "For short-duration releases (e.g., less than 15 minutes), the concentration at the receptor should be calculated as the Time Waited Average (TWA) over the release period, but for no less than 1 minute." For explosions, the release duration should be considered to be 1 minute when calculating the TWA. This is necessary for calculating concentrations of materials when the consequences of concern are concentration dependent versus uptake dependent.

4.3.5.2 SOURCE TERM CALCULATION FOR AN OVERPRESSURE (BLAST EFFECT)

Determining the MAR

The MAR, quantity, form and location, involved in a blast explosion is the material exposed to the shock wave and/or in the proximity. The MAR form is suggested in DOE-HDBK-3010-94 and presented in Table 4.3-2 above. Blast and Fragmentation effects on MAR are calculated.

Determining the DR

The fraction of the MAR impacted by an overpressure or blast effect for all unmitigated scenarios is Damage Ratio (DR) = 1, unless is feasible to apply a standard or technical basis for a different value. Distance, type of explosions, and mitigative and/or design control features are taking into accountability to justify the circumstances (or mitigated scenarios) that predetermined that certain types of material and/or quantity, subjected to the physical stresses, would not be affected by the blast effects.

Determining the ARF/RF

Given the MAR form and the type of effect(s) the material will be impacted based on the explosion, the circumstances, the type of vessel, location, explosive material, abnormal operational conditions. The analyst could select the ARF/RF from the suggested values in Table 4.3-2 above.

Determining the Release Duration

For explosions, the release duration should be considered to be 1 minute when calculating the TWA.

4.3.5.3 SOURCE TERM CALCULATION FOR THERMAL RADIATION

Determining the MAR

The MAR, quantity, form and location exposed to thermal effects, is the material exposed to the thermal radiation in the area on in the proximity of the ignited cloud. The MAR form is suggested in DOE-HDBK-3010-94 and presented in Table 4.3-2 above. Thermal effects on MAR are calculated.

Determining the DR

The fraction of the MAR exposed to the thermal radiation effect for all unmitigated scenarios is Damage Ratio (DR) = 1, unless is feasible to apply a standard or technical basis for a different value. Distance, type of explosions, combustible material, volume, thermal dose and mitigative and/or design control features are taking into accountability to justify the circumstances (or mitigated scenarios) that predetermined that certain types of material and/or quantity, subjected to the physical stresses, would not be affected by thermal radiation effects.

Determining the Release Duration

For explosions, the release duration should be considered to be 1 minute when calculating the TWA.

4.3.5.4 SOURCE TERM CALCULATION FOR FRAGMENTATION

Determining the MAR

The MAR, quantity, form and location subject to impacts from fragmentation, derived from blasts or BLEVEs, is the material reached by fragment(s) over a distance d. The material could be in the nearby proximity directly within the effects of the blast or at various distances, as well as in adjacent rooms separated by physical barriers. The MAR form is suggested in DOE-HDBK-3010-94 and presented in Table 4.3-2 above. Application of TNT methods for assessing the energy impact is appropriate when the MAR is not directly exposed to any of the blast effects discussed above. Fragmentation effects are calculated.

Determining the DR

The fraction of the MAR impacted by fragmentation for all unmitigated scenarios is Damage Ratio (DR) = 1, unless is feasible to apply a standard or technical basis for a different value. Distance, type of explosions, energy deposited at impact, size and mitigative and/or design control features are taking into

accountability to justify the circumstances (or mitigated scenarios) that predetermined that certain types of material and/or quantity, subjected to the physical stresses, would not be affected by the fragmentation effects.

Determining the ARF/RF

Given the MAR form and the consequences from the fragment impact on the material, the analyst could select the ARF/RF from the suggested values in Table 4.3-2 above.

Determining the Release Duration

For explosions, the release duration should be considered to be 1 minute when calculating the TWA.

4.4 SPILLS

Spills are of interest in accident analysis due to their ability to cause an airborne release of radiological materials. As described in DOE-HDBK-3010-94 during a spill event:

> *"Material experiences instability/shear stress at the surface of the mass resulting in sub-division of the overall mass. Airflow patterns around and through the material mass, including induced turbulence, accelerate overall sub-division. Mass breakup is further enhanced by impact with ground surface. The material sub-division can generate particles sufficiently small that they remain airborne for a significant period of time."*

4.4.1 TYPES OF LOSS OF CONFINEMENT/SPILLS AND SCENARIOS

Spills can be defined as the accidental falling or flowing of material out of a confinement boundary. Spills can involve either a closed confinement system (e.g., sealed drum or tank) or an open confinement system (e.g., open container being handled in a GB). The GB, room, and exterior building walls can also be considered confinement barriers, but these barriers are used to determine the leakpath of the spill. Spills can be initiated via human error or an external energy source (e.g. puncture of a container by a forklift or missile, crushing of a container, or drop of container).

DOE-HDBK-3010-94 provides information on the ARF/RF for spills of the following type:

- Free-fall spill of aqueous solutions, 3-m fall distance.
- Free-fall spills of slurries, 3-m fall distance, <40% solids.
- Free-fall spills of viscous solutions, viscosity >8 centipoise.
- Free-fall spills of aqueous solutions, slurries and viscous solutions, fall distances >3 m.
- For the free-fall spill of cohesionless powders <3m.
- For the free-fall spill of cohesionless powders >3m.
- Suspended solid dispersed into flowing air.
- Aqueous solution, slurries, and viscous liquids (non-Newtonian fluids) spilled onto a hard, unyielding surface.

Initiators of Spill

The following type of insults can result in a spill of material:

- Puncture-Perforation;
- Crush-Impact;
- Shock-Vibration; and
- Abrasion.

For liquids and volatile organic compounds, evaporation may be the dominant mechanism for release of hazardous materials. For spills of these types, the surface area of the spill and temperature of the pool dominate the potential release. DOE-Toolbox Codes such as EPICode and ALOHA have pool evaporation models that can be used to evaluate spills of liquids and volatile organic compounds. See Chapter 7 for a further discussion of toxicological consequence analysis.

For spills of gases and cryogenic compounds, the impact on surrounding equipment needs to be considered. Concurrent spills of dissimilar compounds from a common-cause event (e.g., seismic) may result in adverse chemical reactions. Analysis of chemical reactions is discussed in Section 4.5 of this Handbook.

4.4.2 ANALYSIS OF SPILLS

The key to the analysis of spills is to be able to identify the amount of material that is spilled and the mechanical mechanism involved so that the MAR, DR, ARF and RF can be determined utilizing information in DOE-HDBK-3010-94 (this is further discussed in Chapter 5). NUREG/CR-6410, Section 3.2.3.3 *Mechanical Stress*, provides the following descriptions:

A. Puncture-Perforation - of a container or confinement can release materials in a number of ways. For the release of a volatile material, evaporation is the dominant mechanism (Brereton et. al., 1997). Some solids (e.g., phenol) may vaporize/sublime on release from perforated containers. Materials that are flammable gases or have combustible vapors can be vented and, in the presence of an ignition source, result in secondary fires. Solutions with non-volatile solvents and powder may vent if the volume is pressurized and can vent either above the level of the material in the vessel (fragmentation of the liquid by bubble formation and rupture at the surface, or separation of particles at rest by the expansion of the gas in the inter-particle void space) or below it (spray formation of liquids either at temperatures above or below the boiling point of the solvent, or by venting of pressurized volume containing powders). Free-fall spill/release of a solid may be followed by a period of evaporation or even sublimation for volatile solids.

B. Free-Fall Spill (Result of Perforation) - The release and free-fall of liquids and powders can result in suspension from shear stress at the air-material interface. A falling slug can thus shed particles/droplets during the fall. Air resistance can result in the disruption of the face of the falling slug of powder, and particles can be shed into the area of lower pressure resulting from the restoration of the streamlines on the back face of the slug. Impact can induce breakup of solids, powder slugs, and liquids. Volatile materials may evaporate on release (Brereton, et al., 1997).

C. Crush-Impact - This phenomenon imposes force on the surface of the material impacted and can fragment both solids (e.g., brittle fracture, displacement of powders) and liquids (e.g., splashing and droplet formation by displacement and shear). If the force is applied to less than the total surface of the material, fragmentation of the material is limited to the volume that experiences shock wave transmission and reflectance in solids, or the surface area affected for liquids.

D. Shock-Vibration - If the surface is not fragmented, particles lying on the surface (e.g., surface contamination, corrosion products) can be jarred from the surface and suspended by vibratory/shock effects.

E. Abrasion - This phenomenon consists of forces applied to the surface layer that induce fragmentation of the surface by mechanical action. Particles generated may be suspended by the mechanical action more efficiently than by aerodynamic forces.

4.4.2.1 GLOVEBOX SPILLS

Loss of containment inside a GB could be caused by an operator inadvertently dropping an open can of material during an operation such as a bagout operation, or by equipment failure or an airflow reversal. Typically an operator is performing some action in the GB and the spill from a can or bottle occurs as the result of a human error. A chemical reaction could also occur either inside or outside a container, resulting in a container breach. The MAR/DR is the amount of material that could be spilled from the GB. The ARF/RF is determined by the energy of the released material (if any is imparted on it from the release event), height of the release, and atmospheric conditions into which the spill occurs.

4.4.2.2 MATERIAL HANDLING AND WASTE CONTAINER ACCIDENTS

A number of energy sources can cause a spill or loss of confinement during material handling and the movement of waste containers or primary containers with dispersible forms of Pu or U used in processes. The most common include: (1) kinetic energy sources such as maintenance equipment (e.g., drills, grinders), handling equipment (e.g., forklifts), and internally generated missiles (e.g., a bullet from a Security weapon, damaged compressed gas cylinder, or shrapnel from failed rotating plant equipment); (2) potential energy sources (e.g., high storage shelves, elevator shaft, or stairwells); (3) earthquakes; and (4) airplane crashes. In addition, chemical reactions such as nitric acid or chlorinated solvent corrosion of the container and exothermic pyrophoric Pu reactions can also fail the primary confinement boundary. Loss of confinement events involving a single drum, crate, or container can result from all energy sources, typically, during handling operations. Events involving multiple drums, crates, or containers typically require a large energy source from mechanical equipment such as a forklift truck.

Table 4-4 is an example of an approach for defining spill sizes for handling accidents for containers without interior packaging and for tanks/piping. Evaluating different spills sizes may be important if the preventive or mitigative controls that needs to be credited are different, otherwise, the bounding spill size important to establishing the safety basis within a likelihood category is generally evaluated.

Spill sizes, however, depend heavily on spill type, interior packaging, size of packaging, and form and type of hazardous material. For example, the amount of material released from a drum punctured by a fork lift may be different from the amount released from an identical drum that fell from the top of a stack of drums, as in an earthquake. Also, if the material within a container is packaged in additional containers, such as plastic bags, not all of these interior containers would be breached in an accident. A drum puncture, for example, would probably breach only one interior container, so that the amount of spilled material would be reduced by a factor equal to the number of bags in the drum, assuming each bag contains the same amount.

Table 4-4. Spill Sizes for Handling Accidents.

Spill Size	Drums	Tanks/Piping
Small	one drum	≤10% content of tanks/piping
Medium	Two to three drums	>10% but <50% content of tanks/piping
Large	≥ four drums	100% content of tanks/piping

4.4.2.3 OVER-PRESSURIZATIONS

Over-pressures can result from a build-up of pressure in a container through increasing temperature or through radiolysis, and from the pressure wave of an explosion. For a pressurized container, a small hole in the vessel can result in a spray release of liquid or powder whereas a rupture of the container of powder would release a cloud of powder. Explosions are discussed in Section 4.3 and will not be discussed further here.

4.4.2.3.1 PRESSURIZED POWDER RELEASES

If the gases in and around a powder are compressed, the gases will expand rapidly during a sudden release of pressure, resulting in airborne dispersal of the powder. Experiments involving the venting of pressurized powders is discussed in Chapter 4 of DOE-HDBK-3010-94, in which different amounts of powders are subjected to sudden venting under a variety of over-pressures. In general, the larger the over-pressure the larger the amount of powder that becomes airborne.

4.4.2.3.2 PRESSURIZED LIQUID RELEASES

Venting of Pressurized Liquids. There are three main regimes of pressurized venting of liquids: (1) venting below liquid level, (2) venting above liquid level, and (3) venting of superheated liquid (i.e., flashing spray). This phenomena covers general pressurized venting, including deflagration induced pressurized venting effects. Experiments involving the venting of pressurized liquids is discussed in Chapter 3, Liquids, of DOE-HDBK-3010-94.

4.4.2.4 AERODYNAMIC ENTRAINMENT

Aerodynamic entrainment needs to be considered in two situations: (1) air flow past material spilled on the floor or ground, and (2) backdraft of a confinement ventilation system.

Air and other gases passing over a surface or directed onto a surface can induce flow and turbulence that can suspend particles on or from the surface impacted. The presence of obstructions around or over the surface can affect the air flow and, therefore, the suspension of materials from the surface. Sources for gases at accelerated velocities are the passage of or impact by the pressure impulse generated by explosions, ambient wind conditions, or other conditions. In this Handbook, the approach has been to consider aerodynamic entrainment or resuspension[12] conditions as best evaluated for quantification of hazardous release scenarios using empirical relationships based on field and laboratory data. While the transport phenomena described in the Appendix E and in Chapters 6 and 7 are applicable to these situations and improve the understanding of the effects of these phenomena, the reader is directed to Chapter 5 for quantitative inputs applicable to the accident conditions being addressed so that the physical release potential from aerodynamic entrainment/resuspension is conservatively estimated as defined for the DOE-STD-3009 unmitigated analysis. Two scenarios are discussed in more detail.

- Air flow past spilled material: An airborne release rate (ARR), and the length of time that air is flowing past the material, are required to estimate the potential airborne release from postulated accident conditions. In some situations, the release rate may not be uniform with time.
- HVAC backdraft (or flow reversal): For the airflow reversal scenario resulting from a loss of HVAC Zone I functionality, a GB breach could occur and result in the release of holdup material in the GB and exposed material in open containers within the GB. Since the Zone II Ventilation System is still functional, the rest of the building ventilation system is operating under partial system flow or even near normal ambient conditions depending upon the ventilation system design. Other factors that affect the airflow reversal scenario are the damage ratio for the holdup material and the release duration.

4.5 ANALYSIS OF CHEMICAL REACTIONS

Several specific chemical reactions are of interest in accident analysis due to their ability to contribute to the airborne release of radiological materials in nuclear materials processing and waste management as they can lead to loss of confinement, fire and/or explosions. These include:

- Organic-Based Ion Exchange Resin Reaction;
- “Red Oil” Reaction;
- Organic Reaction Event; and
- Hydroxylamine Nitrate Reaction.

[12] Resuspension as used when referring to the stress caused by an accident or to calculate the airborne source term, refers to the initial suspension of materials from the surface of the particulate mass being affected by the accident stress or air turbulence. This should not be confused with a more limited definition of resuspension used in the Chapter 6 and 7 dispersion analyses that refers to the amount of contaminated materials initially deposited as the plume travels downwind that is made airborne again due to wind effects.

These are discussed briefly in this section and in more detail in Appendix D. This information may be useful in identifying and analyzing chemical reaction events. It may also be useful to determine whether a fire, explosion, or loss of confinement may occur (which can be further evaluated per information provided in Sections 4.2, 4.3, and 4.4 of this Handbook).

4.5.1 ORGANIC-BASED ION EXCHANGE RESIN REACTION

Synthetic ion exchange resins are used in nuclear processing operations such as with plutonium nitrate solutions. The separation and purification processes involve contacting nitric acid solutions with organic materials, it is important that the conditions for safe operation be clearly defined and resolutely maintained.

Under conditions of rapid reaction between nitric acid and organic materials, the nitrogen oxides produced by the reaction are also reactive, and this further tends to accelerate the reaction. The result in a confined system can be rapid and accelerating pressurization, with the resulting hazard of bursting the ion exchange column or vessel. The nitrogen oxides themselves also represent a hazard to personnel.

The presence of a large number of active sites designated to exchange ions accompanied by extensive polymer cross-linking in the overall resin matrix creates an inherent potential for instability in the type of resin used. Under the right circumstances, this instability can be expressed in a wide variety of exothermic reactions. A variety of reactions is possible, but once the thermal excursion reaches an autocatalytic state, an over-pressurization incident of some type is the inevitable result.

Various types of theoretical models for assessing the airborne release have been postulated. Precedents within DOE for source term estimation have used the model of a thermal explosion since this model seems to predict damage that best matches what has been historically observed. The model is based on exothermic resin degradation reactions, including the recombination of plutonium with nitrate. In thermal explosion events, the initial source of the resin exotherm is highly localized. The localized area may dry out the resin and heat it above the resin autocatalytic ignition temperature, at which point the column condition can no longer be stabilized. Accelerated heat and gas generation results in rapid pressure build up to the onset of structural failure of the ion exchange vessel. A pressurized spray of superheated liquid occurs when the vessel fails. The amount of release depends on the failure pressure of the ion exchange column since this will determine the degree of superheat. The ARF increases with higher degrees of superheat. Assuming the properties of water as expressed in the steam tables, a superheat of 50 °C corresponds to 0.76 MPa (110 psia), and a superheat of 100 °C corresponds to 3.1 MPa (450 psia). If the accident occurs with process solutions present, the ARF should be obtained from DOE-HDBK-3010-94, Section 3.2.2.2 for blast effects over the surface of the liquid and Section 3.2.2.3 for venting below or above the liquid surface, and Sections 4.4.2.2 and 4.4.2.3 for blast effects and venting of solids/powders, respectively. Ignition of the dried-out polystyrene resin, whether still in the ion exchange column or packaged as waste, may occur before, during, or after the explosion and represents another potential source term mechanism (1E-2 ARF / 1.0 RF per Table 5-1 of Chapter 5).

4.5.2 "RED OIL" REACTION

The PUREX solvent extraction process (and its variants) uses tri-n-butyl phosphate (TBP) and concentrated nitric acid as two principal components (>70 wt% HNO_3). These components, under certain extreme conditions of heating and nitric acid concentration, can react in an uncontrolled manner that could result in very serious consequences such as over-pressurization and rupture of a vessel, and fire or deflagration of flammable gases generated. The stronger the concentration of the nitric acid, the more violent the reaction. In the absence of heat, or the presence of dilute nitric acid (e.g., 30 wt% HNO_3), this reaction does not occur.

Incidents with TBP and concentrated nitric acid are often referred to as "Red Oil" incidents because of the red oily intermediates that form in the TBP phase in the course of the reaction. The red oily intermediates are nitrated compounds that are flammable and produce significant amounts of NO_x gases. This is similar to the red fumes present with red fuming nitric acid (> 90 wt% HNO_3).

Damaging incidents occurred at Hanford and the Savannah River Site in 1953 (Colven et. al., 1953; Campbell and Mailen, 1998). In each case, TBP solution was inadvertently allowed to enter an evaporator in which a nitrate solution was being concentrated at a relatively high temperature.

The consequences from a TBP/nitric acid runaway reaction ("red oil explosion") can vary significantly depending upon assumed initial conditions and vessel design and other factors which influence the accident progression. Common to all scenarios is the oxidation of TBP by nitric acid or nitrates dissolved in it. Possible scenarios range from benign reactions to intense uncontrolled reactions followed by primary vessel failure and/or flammable gas deflagration. Small-scale reactions between TBP and nitric acid can result in slow reactions similar to boiling and a more reactive scenario. In the slow reaction, the release of radioactivity from the vessel would be very small due to a small airborne and respirable release fraction product of 3E-5 ARF / 1.0 RF (see Chapter 5, Table 5-1 for simmering liquid). In the more reactive scenario in which the solution boils, the fraction of radioactivity released could be as high as 2E-3 ARF / 1.0 RF (see Chapter 5, Table 5-1). See also the DOE-HDBK-3010-94, Section 3.2.2.2 for blast effects over the surface of the liquid and Section 3.2.2.3 for venting below or above the liquid surface.

While proper vent area will ensure process vessel integrity, a pressurized radiological release or free-fall spill of liquids would be expected. Also, the consequences of potential flash fire or deflagration of the vented gases on containment structures should be evaluated as well as radiological source terms based on the type of accident stress. Other sections of Chapter 4 and Chapter 5 provide information for these evaluations.

4.5.3 ORGANIC REACTION EVENT

Nitrated organic compounds are in widespread use as propellants and explosives. The generation or accumulation of such materials in nuclear facilities may present a risk of runaway reaction, loss of confinement, fire or explosion. The materials of primary potential concern include organic compounds containing nitrate or nitrite, but also may concern mixtures of organic material and nitric acid. These materials may be solids, liquids, gels, or slurries.

Waste materials are a particular concern. Once a material is set aside as waste, it is easy to ignore, especially if it is kept in a remote tank or waste drum because of its radioactivity. Such materials may include spent resins, degraded solvents, analytical reagents, lubricants that have been exposed to acid, and the like. In this environment, over a long time, further reactions may occur. For example, the explosion

at Tomsk-7, described in Appendix D, appears to have involved degraded, impure solvent that had been stored for a long time in contact with nitric acid solution in a radioactive environment. The resulting material appears to have been highly reactive toward strong nitric acid.

Another concern is the accumulation of materials in unexpected locations. Decomposition of sulfamic acid during processing has led to the accumulation of ammonium nitrate, a potentially explosive material, in the offgas system. The "red oil" incident in the SRS A-Line involved a situation in which, unexpectedly, the organic phase was denser than the aqueous material in the tank with it, and so settled to the bottom. It was then unknowingly drawn off and sent to a drying kettle, where it decomposed into flammable gases.

Ammonium nitrate ($HNO_3 \cdot H_3N$) is a colorless crystal that is a powerful oxidizer used in commercial explosives. It has a heat of formation of–340 kJ/mol at 25 °C. Ammonium nitrate can undergo a decomposition reaction when heated to 250 °C, and can react with other constitutents are a variety of temperatures. Ammonium nitrate fuel oil is a type of reaction with a maximum energy release at a concentration of 94 percent ammonium nitrate with 6 percent absorbed fuel oil. Ammonium nitrate may reaction with other organics less vigorously at other concentrations.

Dealing with these materials therefore involves locating them, sampling them, and developing safe-handling methods. Each case is likely to be unique. The methods for evaluating the problems are general, however, and have been based on long experience in the chemical industry.

An uncontrolled reaction can occur in waste tanks or drums when organic salts are in contact with nitrate/nitrite salts, high enough concentrations of both exist, and temperatures are above the reaction onset temperature. Decay heat and chemical reactions can lead to waste heating over relatively long periods. Increasing temperatures result when heat is dissipated to the environment at a rate slower than it is generated within the waste. The increase in reaction rate with temperature provides a positive feedback mechanism and can lead to an energetic event. Reactions produce high-temperature gases that pressurize the tank. A tank breach results in a pressurized release of reaction product gases that entrains aqueous tank material.

In the chemical and radiological conditions found in the Hanford Site tanks, organic complexants decompose to low energy compounds such as formate, oxalate, and carbonate (Meacham et. al., 1998). These low energy compounds do not support deflagration propagation (Meacham et. al., 1998). This aging process greatly reduces hazards associated with organic complexants in these tanks.

The radiological source term from an organic reaction is evaluated based on whether the consequences are from a chemical detonation or thermal runaway reaction with rapid generation of gases that could over-pressurize and rupture the vessel or container leading to a high pressure release of the radioactive material. In addition to or instead of a pressurized release of radioactive material, if the vented gases are flammable, the physical consequences of potential flash fire or deflagration on containment structures is evaluated to estimate the radiological source terms based on the type of accident stress. Other sections of Chapter 4 and Chapter 5 provide information for these evaluations, such as use of the TNT model for a detonation, or fire and deflagration release fractions depending on the form of the radioactive material, combustion while suspended in air, unconfined burning after settling, and confined burning within a container.

An example of an organic fuel-oxidizer reaction occurred on February 14, 2014 that caused an airborne radiological release at the Department of Energy Waste Isolation Pilot Plant (WIPP). The DOE Accident

Investigation Board determined that the release was a result of an exothermic reaction involving the mixture of the organic materials (Swheat Scoop® absorbent and/or neutralizer) and nitrate salts present inside a single TRU drum. The drum was remediated and certified to meet the WIPP Waste Acceptance Criteria (WAC) at the Los Alamos National Laboratory (LANL) and subsequently shipped to WIPP for permanent disposal. Chemical reactions resulted in internal heating inside the drum that led to a thermal runaway with an exponential temperature rise in the core and rapid generation of gases (some combustible) which exceeded the drum venting capacity. The drum lid extruded beyond the lid retention ring, deflected the lid, and resulted in a rapid release of the materials from the drum. The combustible gases and solids ignited, which then spread to other combustible materials within the waste array, i.e., fiberboard and polyethylene slip sheets, reinforcement plates, stretch wrap, cardboard stiffeners and polypropylene super sack fabric. The energetic release propelled TRU waste from the drum up into the polypropylene magnesium oxide (MgO) super sacks on top of the container stack, onto adjacent stacked waste containers, and throughout the underground exhaust path from the drum's location. The results of the Phase 2 investigation were issued on April 16, 2015, and are available at: http://energy.gov/em/downloads/radiological-release-event-waste-isolation-pilot-plant-february-14-2014.

See also SRNL-RP-2014-01198, *Waste Isolation Pilot Plant Technical Assessment Team Report*, and LA-UR-15-22393, *Chemical Reactivity and Recommended Remediation Strategy for Los Alamos Remediated Nitrate Salt (RNS) Wastes*, for detailed discussion of the reaction mechanism.

4.5.4 HYDROXYLAMINE NITRATE REACTION

Hydroxylamine, NH_2OH, has been used in the nuclear industry as a reducing agent and in decontaminating solutions. It is used as the nitrate (HAN) or sulfate (HAS) salt in solution. It has the advantage of reducing plutonium smoothly to the trivalent state without creating potential solid waste.

Hydroxylamine is unstable against decomposition in the presence of nitric acid, and this reaction is catalyzed by dissolved iron. This reaction occurs more readily at higher nitric acid concentrations. It appears that the formation of nitrous acid is an important element in the mechanism. This reaction, once begun, can accelerate to a dangerous rate, producing great quantities of gas and pressurizing containers. At least seven damaging incidents involving the decomposition of HAN have occurred in DOE facilities. The last of these occurred in May 1997 at the Plutonium Reclamation Facility in Hanford. An authoritative report on hydroxylamine nitrate in nuclear facilities has been published, and this section is drawn from that report (DOE/EH-0555, 1998).

Since the vented gases are not flammable, the radiological source term from decomposition of HAN that results rapid generation of gases that could over-pressurize the vessel or container is based on a pressurized release of the solution.

4.5.5 ADDITIONAL COMMENTS ON CHEMICAL REACTIONS ACCIDENT ANALSYSIS IN A DSA

Estimating the consequences from plausible scenarios that have radioactive materials involved in a chemical process to accident analysis in a DSA may be challenging. One could evaluate a loss of confinement and/or a fire or explosion event as separate or combined events. For example, if a process with plutonium dissolved in nitric acid has a loss of confinement event and the vessel loses enough liquid such that the plutonium in solution dries and is exposed to ambient oxygen, then the risk of a pyrophoric fire exists after the loss of confinement event. Consider the radiological and chemical consequences with any event involving radioactive material involved in a chemical reaction accident.

For a thorough evaluation, one could consider the source term parameters that provide a conservative conclusion that drive a control set. Changing the parameters by an order of magnitude may not change the conclusion or the resulting control set.

For example, consider a damage ratio of one for resin columns, waste drums or process vessels. Consider the total MAR in the vessel for the combined loss of confinement and fire or for an explosion of a vessel. Consider accident progression from loss of confinement to fire or explosion and combine into a single accident with a range of ARF/RF in the range of 1E-2 to 1E-4, which approximates the information from the DOE-HDBK-3010-94 information for these type accidents, as summarized in Chapter 5 of this Handbook.

By using a bounding MAR of the entire vessel contents, a DR of one, an ARF/RF in the range of 1E-2 to 1E-4, and a LPF of one, a conservative accident analysis can be described in a DSA. If the resulting consequence driven control set can enable safe operations without being too difficult to implement, then the source term parameters used may suffice. Only if further refinement in a particular parameter is needed to reasonably reduce consequences to receptors do the accident analyses warrant such refinements. If the postulated event in the DSA closely resembles an event that has either happened in the past or has been analyzed in a technical journal or report, then this information can be used to technically justify the DR, ARF, and RF.

This suggestion is not meant to override explicit source term parameter values documented in literature elsewhere in this or in other documents.

4.6 NATURAL PHENOMENA EVENTS

Natural phenomena hazard (NPH) events are of interest in accident analysis due to their ability to contribute to the airborne and/or waterborne release of radioactive and toxic chemical materials that may result when SSCs fail to perform their safety function during and after the NPH events. Furthermore, the NPH events may cause fire or explosion that could provide energy for transporting the radioactive and toxic chemical material and at the same time degrade the functions of the SSCs.

4.6.1 NPH EVENT TYPES

An NPH event is also of interest in evaluating the effectiveness of the control set SSCs, as well as in evaluating the response actions of the controls that are relied upon.

The NPHs that are of interest for most DOE Sites are:

- seismic events (earthquakes),
- extreme winds (straight-line winds, tornadoes, and hurricanes),
- floods (including seiches and tsunamis),
- extreme precipitation (including snow and rain),
- lightning,
- volcanic eruptions, and
- wildland fires.

DOE-STD-1020-2012, *Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities*, provides criteria and guidance for HA and design for these NPHs, except wildland fires, which is addressed in DOE-STD-1066-2012, *Fire Protection*. Additional guidance to implement DOE-STD-1020-2012 is being developed in the draft DOE-HDBK-xxxx-2016, *Natural Phenomena Hazards Analysis and Design Handbook for DOE Facilities*. There may be other NPHs that may be applicable for certain sites, but no guidance for HA or design for these NPHs is provided in either DOE-STD-1020-2012 or DOE-STD-1066-2012. These NPHs include drought, fog, frost, extreme temperatures, landslides, subsidence, surface collapse, uplift, and waterspouts. For these NPH events, DOE-STD-1020-2012 recommends that facility operators discuss with DOE which, if any, of these NPHs need consideration, based on both site-specific NPH and site facility characteristics.

4.6.2 NPH EVENT ANALYSIS OVERVIEW

Unmitigated accident analysis of NPH events is performed differently for safety basis documents for new nonreactor nuclear facilities and major modifications to existing nuclear facilities, than for existing facilities where the DSA is to be updated as a result of revised NPH criteria based on periodic reassessments. These approaches are addressed in the following subsections, followed by a summary of the general methodology for these evaluations.

4.6.2.1 ACCIDENT ANALYSIS FOR NEW NUCLEAR FACILITY OR MAJOR MODIFICATION DSA

In preparing a safety design basis document (e.g., CSDR or PDSA) for the purpose of designing a new nuclear facility, the evaluation of NPH events is different from the evaluation of operational accidents because the magnitude of a design basis NPH event (e.g., the peak ground acceleration from an earthquake, or the wind speed of a tornado) is determined based upon: (a) the unmitigated dose consequences of the SSC failure that determines the NPH design category (NDC) of an SSC and the associated performance goal (expressed as annual probability of failure), and, (b) a factor that is a measure of the degree of inherent conservatism in the design criteria and analysis methods specified for the NDC of the SSC in DOE-STD-1020-2012 and supporting industry standards.

For new facilities, the NDC of an SSC establishes a risk-based target performance goal for the SSC, and the return period[13] of the specific hazard, given in DOE-STD-1020-2012, to which the SSC will need to be designed. The NDCs were formerly called Performance Categories (PCs) in previous versions of the DOE design-related orders, guides, and standards, which are roughly equivalent from a performance goal

[13] The return period is the reciprocal of the frequency of occurrence or likelihood of the NPH event, e.g., a 100-yr flood has a 1E-2/yr frequency of occurrence or is considered to have an unlikely likelihood per Table 2-9, Qualitative Likelihood Classification.

perspective to the numerical assignments for NDC [e.g., a PC-3 SSC is a similar concept as a Seismic Design Category (SDC)-3 (SDC-3)] SSC.

DOE-STD-1189-2008 provides further guidance on accident analysis for developing safety basis design documents. In general, for safety analysis of a new facility or major modification to an existing facility, SSCs in a nonreactor nuclear facility are designed for the appropriate NPH events, defined by their return periods, applicable for the NDCs of the SSCs. The unmitigated dose consequences of the SSC failure that determines the NDC of an SSC is based on the CW at 100 m and offsite public criteria as provided in Appendix A to DOE-STD-1189-2008, and the additional guidance in ANSI/ANS-2.26-2004 (R: 2010), *Categorization of Nuclear Facility Structures, Systems and Components for Seismic Design*, as modified by the discussion in DOE-STD-1189-2008 Appendix A. DOE-STD-1020-2012 extends the radiological consequence criteria in DOE-STD-1189-2008 Appendix A to non-seismic NPH events. Subsections 4.6.3 through 4.6.8 address additional guidance on unmitigated analyses of specific NPH types to estimate radiological and toxic chemical source terms based on conservative estimates of MARs and DRs. Atmospheric dispersion and radiological dose calculations are performed in accordance with Chapter 6 of this Handbook. To determine MARs and DRs for safety classification and NDC categorizations of the SSCs during a new facility design, the unmitigated consequence analysis should assume that the building structure inside which the SSCs are located would not maintain confinement and may collapse during the design basis NPH event.

Section 2.1.5 of DOE-STD-1020-2012 recommends that, for NPH design of non-nuclear facilities containing "significant" toxic chemical hazards, the nuclear facility guidance and criteria in Section 2.3.9 of the standard be considered. This provision of the standard is amplified in Section 2.3.9, "Additional Guidance for Hazard Category 1, 2, and 3 Nuclear Facilities with Chemical Hazards," of the draft DOE-HDBK-xxxx-2016. Additional guidance on what is considered "significant" is also provided there. The NDC for SSCs that provide protection from toxic chemical hazards are determined based on the unmitigated consequences of SSC failure from an NPH event, similar to the unmitigated consequence methodology for radiological releases. The methodology for this unmitigated analysis should be consistent with DOE-STD-3009-2014 and Chapter 7, *Chemical Dispersion and Consequence Analysis*, of this Handbook, to determine the need for SS SSCs which influences the NDC determinations. DOE-STD-1020-2012 recommends the higher of the NDCs determined from the application of radiation dose criteria and the criteria for toxic chemical consequences be used; therefore, it is possible that an SSC categorized as NDC-2 based on radiation hazards may be assigned to the NDC-3 category based on toxic chemical hazards. The Limit State, as defined in ANSI/ANS-2.26-2004 (R: 2010), should be chosen to be consistent with safety and containment criteria.

4.6.2.2 ACCIDENT ANALYSIS FOR EXISTING NUCLEAR FACILITY DSA

For existing facilities, the NDC establishes the return period of the specific NPHs to which the SSC design will need to be evaluated. For the DSA evaluation of NPH impacts on existing facilities, the initial step is to establish, for each SSC, which NDC from the guidance in DOE-STD-1020-2012 should apply, or which PCs from the previous DOE standards apply as discussed below. Evaluations of SSC capacities should have already been performed utilizing the current or previous versions of DOE-STD-1020-2012 and other related NPH standards and guides, which at that time would have required an implementation plan and integration with the safety basis process, when required by the DOE Program Secretarial Office per DOE O 420.1B or 420.1C.

As stated above, the appropriate NPH NDCs or PCs for evaluation to support the DSA upgrade for the existing nuclear facility is initially determined. DOE O 420.1C and DOE-STD-1020-2012 require that

sites with any facilities rated NDC-3 or higher review existing NPH assessments at least every 10 years. DOE-STD-1020-2012 provides criteria and guidance to conduct such a review. If the review determines a new assessment is necessary, this assessment could potentially trigger design and safety basis reviews of existing facilities if significant increases in NPH design loads or risks are identified. Any previous evaluations of SSCs should be updated using the new NPH information resulting from the 10-year reassessment requirement. The results of the updated evaluations should be used in the unmitigated radiological and toxic chemical consequence evaluations to support any required updates of the accident analyses. If increased NPH loads exceed the capacity of existing SSCs, the DOE Site Office would evaluate and determine whether to upgrade SSCs and whether such evaluation results need to be integrated with the DSA annual update.

A 10-year NPH review may conclude that the existing NPH assessment is adequate. If the existing assessment is deemed deficient and a new NPH assessment is completed, the new NPH loads might be within the DBA and EBAs already evaluated in the DSA. For upgrading an existing facility DSA to DOE-STD-3009-2014 when the NPH loads are not increased, the originally-established NPH DBAs or EBAs defined in the currently approved DSA should continue to be evaluated. Accordingly, the unmitigated accident analysis is based on applying what is already evaluated in the current DSA (e.g., the NDCs from DOE-STD-1020-2012, or the PCs from DOE-STD-1020-2002, *Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities*). If DOE-STD-1020-2002 is the basis for the evaluation, the PC determination is made in accordance with DOE-STD-1021-93 (R: 2002), *Natural Phenomena Hazards Performance Categorization Guidelines for Structures, Systems, and Components*. DOE-STD-1021-93 assigns PC-3 to SC SSCs and PC-2 to SS SSCs, based on the unmitigated consequences for the applicable NPH events, rather than the DOE-STD-1189-2008 criteria (e.g., NDC-3 if doses exceed 25 rem to the public or 100 rem to the CW at 100 m). Application of the previous DOE NPH standards and other DOE NPH guides for upgrading the DSA to DOE-STD-3009-2014 is allowable based on:

1. DOE Order O 420.1C, Chapter I, Nuclear Safety Design Criteria, Section 2 Applicability, that only applies to design of new nuclear facilities or major modification to existing facilities;
2. DOE O 420.1C, Chapter IV, Natural Phenomena Hazards Mitigation, Section 2 Applicability, for situations involving "modifications that may be warranted based on periodic NPH assessment and upgrade requirements," when the DOE Program Secretarial Office determined that existing facilities need not be evaluated to higher NPH loads; and,
3. DOE-STD-1020-2012, Foreword, and Section 1.2, Background, that the superseded standards will still be available for reference and use at existing facilities and can be found at the archived standards section of the DOE Technical Standards Program website.

If a new NPH assessment yields increased NPH loads, the DOE-STD-1020-2012 Section 9.3, Facility Condition Assessments, allows for a factor of two reduction in the return period and lesser design loads, with caveats, when evaluating existing SSCs. Additional guidance for evaluation of existing facilities to increased loads is included in Section 9 of the DOE-HDBK-xxxx-2016. If a new NPH assessment increases the site's NPH loads and an engineering evaluation concludes that the existing structure will not withstand the current DOE O 420.1C DBA criteria, with allowances, a collapse event should be further evaluated in DSA Chapter 3 accident analysis as an EBA.

In performing an NPH engineering evaluation for the existing facility, an unmitigated dose consequence analysis is required to be performed that would assume that the structure will suffer major damage and/or will collapse. The resulting unmitigated dose will be compared with those in the DOE-STD-1189-2008

Appendix A criteria to determine the appropriate NDC level. Chemical consequences can be evaluated the same as discussed for new facilities or major modifications described in Section 4.6.2.1.

When an NPH engineering evaluation of a building structure to the revised NPH loads concludes that the building structure will not be deformed more than Limit State C (see ANSI/ANS 2.26 and ASCE/SEI 43-05, *Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities*), the building structure can be credited to maintain confinement and not collapse per the guidance for unmitigated analysis in Section 3.2.2 of DOE-STD-3009-2014. However, if other SSCs fail at the revised NPH loads, the unmitigated dose consequence analysis should recognize that some damage to other SSCs, such as fire sprinklers, may occur and could cause collateral damage resulting in potential radiological or hazardous chemicals releases.

The unmitigated radiological and chemical consequences of the SSC failure that determines the NDC of an SSC is based on the same criteria and methods described above for evaluation of new facilities and major modifications, and guidance from other chapters of this Handbook. Subsections 4.6.3 through 4.6.8 address additional guidance on unmitigated analyses of specific NPH types to estimate radiological source terms based on conservative estimates of MAR and DRs.

If the DOE Site Office has determined that an implementation plan for evaluation of existing SSCs is not required per DOE Order O 420.1C and DOE-STD-1020-2012 because 10-yr reviews of all applicable NPHs, performed following DOE-STD-1020-2012 requirements, have concluded that (1) the original DBAs developed for the design of the facility, or (2) EBAs established per previous DOE Order O 420.1C requirements for evaluation of existing facilities, are bounding, then a DSA revision should:

1. document that the updated NPH evaluations did not change the existing accident analyses in the safety basis document. If the SC and SS SSCs have been concluded to provide their safety functions for the applicable NPH EBA criteria for existing facilities, their failure during a higher level NPH event is considered to be a Beyond DBA and therefore the consequence of their failure does not have to be considered in the DSA Chapter 3 accident analysis, except in regards to potential cliff edge effects associated with evaluation of Beyond DBAs (addressed in the next bullet).

2. evaluate SSCs for Beyond DBAs using NPH event return periods applicable for NDCs one level higher than the design or evaluation basis NDCs. For example, if the design or evaluation basis NDC of an SSC is NDC-3, its Beyond DBA can be defined using a return period applicable to NDC-4. See Section 3.4, Beyond Design/Evaluation Basis Accidents, of this Handbook for further discussions.

For existing facilities, all SSCs, including confinement barriers, that have been evaluated to meet the requirements of DOE-STD-1020-2012, can be credited for determining the NPH loads or demands on other SSCs, if the NDCs of these other SSCs are the same as or lower than the former SSCs. For example, in determining the wind loads on a Wind Design Category (WDC) WDC-3 glove box inside a concrete building, the mitigating effects of the building can be credited provided the evaluation of concrete building indicates that the building can withstand the WDC-3 wind loads. However, such credit for WDC-3 building cannot be taken while determining the WDC of the glove box, because WDC determination is done based on unmitigated consequences of failure of the glove box.

4.6.2.3 GENERAL METHODOLOGY

For preparing the DSA of a nuclear facility, the list of DBA/EBAs would include those resulting from NPH events. The selection of the size of these NPH events and their evaluation and mitigation are required to be performed in accordance with DOE-STD-1020-2012, the application of which involves the following four general steps:

1. Perform an unmitigated radiological, and if applicable chemical, consequence analysis using guidelines given in DOE-STD-1020-2012, including those given in ANSI/ANS 2.26 and Appendix A of DOE-STD-1189-2008, and this Handbook. Consequence analysis should also consider reasonable secondary events (e.g., seismic induced fire). Identify the highest NDC that corresponds to the consequences calculated in the unmitigated consequence analysis.

2. Identify the SSCs whose individual failure contributed significantly to the unmitigated consequence calculated in Step 1 above, and designate these SSCs at the highest NDC. Designate the other SSCs at a lower NDC depending upon their failure's contribution to the unmitigated consequences. The cumulative dose resulting from the simultaneous failure of this second group of SSCs must be less than the dose threshold for the highest NDC of the above first group of SSCs. If not, one or more of the SSCs in the second group shall be upgraded to the first group, i.e., they will be designated to the highest NDC.

3. Identify the size of the NPH event (return frequency and associated NPH design parameter, such as ground motion) based upon the NDC of the SSCs following DOE-STD-1020-2012 requirements.

4. Design or evaluate the SSCs for the NPH loads associated with the NDC of the SSC.

DOE-HDBK-xxxx-2016 provides guidance and clarifications for implementing the requirements given in DOE-STD-1020-2012 for performing the above four steps. In general, for all nuclear and hazardous facilities in the DOE complex, DBA/EBAs related to NPH events are evaluated using criteria and guidelines given in DOE-STD-1020-2012. However, for TRU facilities, some NPH event evaluation guidance is provided in DOE-STD-5506-2007. Since the NPH evaluation provisions in DOE-STD-5506-2007 were developed independent of those in DOE-STD-1020-2012, therefore, during the DSA development process, some inconsistencies between the provisions in these two documents may be identified. Any such identified inconsistency should be reported to the DOE with proposed resolution.

SSC failures from NPH events may also cause chemical releases from nonreactor nuclear facilities with chemical hazards requiring further DSA evaluation as described in Section 2.4.6, Chemical Hazard Evaluation. NPH-induced chemical releases are evaluated similar to other operational accident types as described in Section 3.1 Accident Type Selection. For example, an NPH event can cause spills of process solutions or powders and result in impacts of debris on process equipment or impact of process equipment with the floor, or potential fires or explosions. The DR, ARF and RF are typically as they are for those operational accidents. Care should be taken to determine if the effect of the NPH will cause abnormal process conditions. These types of events should be identified and analyzed in the DSA. For example, it might be more conservative to assume that a process tank remains intact, but suffers an overpressure event due to lack of power or cooling. Failure of tanks or vessels could result in energetic chemical reactions which may cause a release. Rupture of a line could result in a spray release.

The rest of Section 4.6 is organized per the NPH type as identified in Section 4.6.1.

4.6.3 SEISMIC EVENTS

Seismic events result in ground motions that can affect all the SSCs in a facility, so the unmitigated consequences of all the SSCs in the facility should be considered. The seismic ground motions result in accelerations and displacements that are transmitted into the facility structure and to all the systems and components in the facility structure. Seismic events can also result in ground displacements that can impact the behavior of the facility structure foundations and result in failures. The facility's foundations should be evaluated to address any potential structural concerns. Seismic events can cause secondary events, such as failure of ground slopes near the facility structure, tsunamis, and seiches, which can result in additional flooding concerns, facility fires, explosions, deflagrations, and unwanted interaction between SSCs in the facility.

Additional discussion of the seismic events is provided in Chapter 3 of the DOE-STD-1020-2012 and DOE-HDBK-xxxx-2016. The unmitigated accident analyses performed for the facility determines the SDC of the SSCs which defines the size of the seismic event to be used to design/evaluate the facility SSCs.

The accident analyses for the seismic event are performed in accordance with DOE-STD-3009-2014 and DOE-STD-1189-2008 to determine the unmitigated consequences of release of the radiological and/or toxic chemical materials contained in the facility. As stated above, the results of the accident analyses determine the SDC for the facility SSCs.

Seismic events can affect all of the SSCs in a facility; therefore the unmitigated failure consequences of each affected SSC in the facility should be analyzed. The simplest evaluation of the unmitigated consequence assessment is to consider all hazardous material to be released in a seismic event (i.e., DR = 1), but this may not be necessary in all situations. The analyst needs to justify analyses that do not make this conservative assumption.

Some SSCs may be inherently rugged and able to resist seismic events (see ANSI/ANS-2.26-2004 (R: 2010) for determining ruggedness) and the seismic failures of other SSCs that could impact the inherently rugged SSCs. Earthquake experience information or previous seismic evaluations of similar SSCs may be used to estimate the extent of MAR and DR for each rugged SSC. These judgments of damage, MAR, and DRs should be determined working with the discipline engineers responsible for the seismic design and evaluation. Accordingly, to analyze the seismic event, the analyst should:

1. Define the scenarios;
2. Identity the type of material involved and appropriate DRs;
3. Determine the unmitigated consequences;
4. Determine the SSCs which will be used to mitigate the consequences; and,
5. Define the SDC for the SSCs that mitigate the consequences.

4.6.4 EXTREME WIND EVENTS

Extreme wind events can be “straight-line”, “tornado”, or “hurricane”. Straight-line winds are non-rotating winds that cover a wide area, typically many tens of miles across, and can reach speeds in excess of 100 mph (160 km/hr). They are generally associated with thunderstorms, derechos, and mesocyclones. Tornadoes are violently rotating winds that are very localized which are a few miles or less across, and can reach speeds in excess of 200 mph (320 km/hr). This type of atmospheric phenomenon commonly accompanies other severe weather extreme wind events (i.e., thunderstorms hurricanes). Tornadoes all cause significant atmospheric pressure changes (APCs) within its vortex. Hurricanes are very large-scale rotating winds, typically hundreds of miles across; by definition, hurricane wind speeds are in excess of 74 mph (119 km/hr). Wind-generated missiles can also result from extreme wind events which have to be considered in the extreme wind design and evaluation.

Extreme wind speeds can potentially damage buildings and other structures in a variety of ways. Loose objects picked up by the extreme wind can become missiles that can penetrate a SSC. The roof covering and siding material can be blown off of the building and extreme winds passing sharp corners of the building tend to separate from the building, causing an outward pressure. In general, the windward surfaces of the building experience an inward pressure and all other exterior surfaces experience an outward pressure. Likewise, the internal air pressure can rapidly change if air can pass into or out of a structure through openings, such as those caused by a wind-driven missile. If the opening is on the windward side of the building, the internal pressure increases, which reinforce the outward pressures of the outside air on the other surfaces. If the opening is on any other side of the building, the internal pressure decreases, which counteract the outward pressures of the outside air. In any case, if the APC exceeds the structural strength of the building, the building can suffer significant damage.

Additional discussion of all extreme wind events is provided in Chapter 4 of the DOE-STD-1020-2012 and the DOE-HDBK-xxxx-2016. The accident analyses performed for the facility determines the Wind Design Category (WDC) of the SSCs, which defines the size and return period of the extreme wind event to be used to design and evaluate the facility SSCs.

The accident analyses for the extreme wind event are performed in accordance with DOE-STD-3009-2014 and DOE-STD-1189-2008, based on the unmitigated consequences of release of the radiological and/or toxic chemical materials contained in the facility. As stated for seismic events, the results of the accident analyses determine the WDC for the facility SSCs.

For extreme wind events, if properly designed in accordance with the requirements of DOE-STD-1020-2012, the facility structure can usually be considered to protect the systems and components inside of it. This is dependent on the number of openings in the facility structure which could result in internal wind-induced pressures on the systems and components inside of it. The facility structure’s failure should be considered in determining the unmitigated consequences of the release of the hazardous material to the environment. As discussed for seismic events, some SSC’s inside the facility structure may be inherently rugged (see ANSI/ANS-2.26-2004 (R: 2010)) for determining ruggedness) and able to resist the extreme winds and its associated missiles. Wind experience information or previous wind evaluations of similar SSCs may be used to estimate the extent of MAR and DRs for such rugged SSCs. These judgments of damage, MAR and DRs should be determined working with the discipline engineers responsible for the wind design and evaluation.

SSCs located outside of the facility structure are also susceptible to the extreme winds and associated missiles. The failure of these SSCs should also be considered in the accident and consequence analyses.

To analyze the wind event, the analyst should:

1. Define the scenarios;
2. Identity the type of material involved and appropriate DRs;
3. Determine the unmitigated consequences;
4. Determine the SSCs which will be used to mitigate the consequences; and,
5. Define the WDC for the SSCs that mitigate the consequences.

4.6.5 FLOOD AND PRECIPITATION EVENTS

Flood events for a facility can result from several sources, such as river flooding, dam, levee, or dike failure, storm surge, tsunami, seiche, landslide, extreme precipitation (i.e., both rainfall and snow/ice) run-off, and extreme precipitation loading on roofs or outside utilities. Floods can also cause water-borne debris impacts which should also be considered.

Additional discussion of the flood and extreme precipitation events is provided in Chapters 5 (flood) and 7 (extreme precipitation) of DOE-STD-1020-2012 and the DOE-HDBK-xxxx-2016. The unmitigated accident analyses performed for the facility determines the Flood Design Category (FDC) of the SSCs which defines the size of the flood event to be used to design/evaluate the facility SSCs. For dry sites, which are defined as sites that have no external flood threat outside of extreme precipitation, the unmitigated accident analyses performed for the facility determines the Precipitation Design Category (PDC) of the SSCs which defines the size of the extreme precipitation event to be used to design/evaluate the facility SSCs.

The accident analyses for the flood and extreme precipitation events are performed in accordance with DOE-STD-3009-2014 and DOE-STD-1189-2008 based on the unmitigated consequences of release of the radiological and/or toxic chemical materials contained in the facility. As stated for seismic and extreme wind insults, the results of the unmitigated accident analyses determine the FDC and PDC for the facility SSCs.

For flood and extreme precipitation events, if properly designed in accordance with the requirements of DOE-STD-1020-2012, the facility structure can usually be considered to protect the systems and components inside the facility structure. This is dependent on the number of openings in the facility structure which could result in inflow of flood water. The facility structure's failure should be considered in determining the unmitigated consequences of the release of the hazardous material in the facility. As discussed for seismic events, some SSC's inside the facility structure may be inherently rugged (see ANSI/ANS-2.26-2004 (R: 2010) for determining ruggedness) and able to resist the flood and extreme precipitation events. Flood and precipitation experience information or previous flood and precipitation evaluations of similar SSCs may be used to estimate extent of MAR and DRs for such rugged SSCs. These judgments of damage, MAR and DRs should be determined working with the discipline engineers responsible for the flood and extreme precipitation design and evaluation. Some SSCs, even though capable of withstanding mechanical loads from flood water, may fail to perform their safety function when subjected to water intrusion or inundation. These modes of failure should also be considered in performing flood and extreme precipitation hazard evaluations.

SSCs located outside of the facility structure would be susceptible to the flood, extreme precipitation, and associated water debris. The failure of these SSCs should also be considered in the accident and consequence analyses.

To analyze the flood and precipitation events, the analyst should:

1. Define the scenarios;
2. Identity the type of material involved and appropriate DRs;
3. Determine the unmitigated consequences;
4. Determine the SSCs which will be used to mitigate the consequences; and,
5. Define the FDC and PDC for the SSCs that mitigate the consequences.

4.6.6 LIGHTNING EVENTS

Chapter 6 of the DOE-STD-1020-2012 and the DOE-HDBK-xxxx-2016 do not provide a detailed discussion about the effects of lightning events, nor provide graded design criteria. Accordingly, the following additional guidance is provided.

Lightning is a high-current electrical discharge in the atmosphere with a path length typically measured in kilometers. Natural lightning is almost always associated with clouds, normally those of weather (e.g., thunderstorms, hurricanes), but can also be present in volcanic clouds and clouds from dust storms (haboobs).

It is important to assess the severity and frequency of lightning strikes at a site since lightning can:

- Start a fire inside a building, outside of a building but within the industrial area, or on the area surrounding the industrial area of a site; fire can also arise from contact of combustibles with a lightning-heated non-combustible;
- Breach a building, providing an open pathway for radioactive or other hazardous substances to be released into the atmosphere. Because filter plenums are electrically conductive, they can attract lightning and can therefore be breached by lightning even within a building. This would provide another leak path to the environment as well as to personnel within the building; and,
- Cause sensors to fail or give false alarms, cause communications and electronic component failures, and cause power failures, which give rise to other system failures.

The analyst can consult the isokeraunic map[14] of the United States given in the Lightning Protection Code, NFPA 780 (NFPA, 1992). Hasbrouck (1995) presents a methodology for estimating the density of lightning flashes at a given location, based on the number of thunder days per year and the latitude of the site. Using the number of thunder days per year, the analyst needs to derive the average flash density at the DOE site in question. From this flash density information, an estimate of the number of lightning strikes in both the inner portion of the site (i.e., industrial area) and the entire site can be developed.

The severity of a lightning flash is usually defined by the peak amplitude of its return stroke current, which range from one to hundreds of kA. The upper one-percentile current (i.e., 99 percent of all lightning flashes have a lower current) has been determined to be about 200 kA. Lightning scientists identify this level of currnt as the severe threat level. The 50th percentile value lies in the 20-30 kA range.

[14] A thunder day, according to the NFPA 780 Lightning Protection Code, is a day in which a trained observer hears thunder; the thunder can arise from either inter-cloud or cloud-to-ground lightning. The number of occurrences of thunder during the day is not a factor. A storm that produces lightning but no thunder is not counted. An isokeraunic map is a map that shows contours of equal numbers of thunder days per year.

For flat terrain without buildings or other structures, the probability of a lightning strike is the same throughout the area. However, structures, especially tall ones such as stacks, water towers, and power poles, attract lightning and increase the probability of a strike at those locations, thus decreasing the probability at other nearby locations. These taller structures provide some protection for the shorter structures nearby. The "circle of protection" offered by a tall structure depends upon its height and the peak current in the lightning strike. As a rule of thumb, for a medium-current strike, the radius of the circle of protection is equal to the height of the grounded lightning attractor. However, this is not valid for all lightning as the radius of the circle of protection also depends upon the current in the lightning strike (i.e., the larger the current, the larger the circle of protection). A building that may be protected by a larger nearby structure for a high-current lightning strike may not be protected from a lower-current strike. Elevated conducting wires that are horizontal and grounded can also protect facilities below them. Power lines could therefore be considered to provide some protection for certain buildings. In general, the stacks, water tower, and power lines may offer protection for only a small portion of an industrial area.

If a particular facility is not protected, the expected number of lightning strikes per year can be determined by multiplying the footprint area of the facility by the lightning strike density. If this facility has a life expectancy before Decontamination & Decommissioning longer than five years, it may suffer one lightning strike sometime during its remaining life if no lightning protection is provided. If National Fire Protection Association (NFPA)-specified lightning protection is provided, the likelihood of lightning damage is, of course, greatly reduced.

It should be emphasized that not every lightning strike is damaging. The amount of damage depends on the amount of current in the return stroke, the magnitude of any continuing current, and the susceptibility of the target to lightning damage. Electronic equipment, for example, is more susceptible to failure from a lightning strike than a concrete pad is to fire damage. The main danger from lightning for the site is from fire, as fire can potentially lead to a release of radioactive or toxic chemic material. Lightning-induced fire can be caused in several ways:

1. Fire can be started in dry combustible material, such as a wooden structure or dry grass, by the weak "continuing current" between lightning strokes.[15] About 20 percent of the lightning strikes have a continuing current large enough to start such a fire (Hasbrouck, 1989). The magnitude of the peak current is not relevant here, as the return stroke is too brief to start a fire. This type of fire will be mainly confined to wildland fires and wooden power poles, unless there are wooden structures on the site and no requirement that any wood brought onto the site be treated with fire retardant. Range fires can occur only when the wildland grass is dry. Lightning-induced wildland fires are anticipated. In addition, power poles have been set on fire by lightning, showing that this type of fire must also be considered anticipated.

2. If a facility is constructed of non-combustible building materials, a so-called Highly Protected Risk (HPR) facility, the frequency of a lightning-induced in-facility fire is *extremely unlikely*, whether or not the facility has a properly functioning lightning protection system.

[15] The continuing current will probably not start a fire within a concrete structure or Butler-type building.

3. For non-HPR facilities, a one order of magnitude frequency reduction may be taken for lightning-induced in-facility fires if the facility has a lightning protection system that can perform its designed function as determined by Fire Protection Engineering.

4. A lightning strike on a building can induce large currents in the electrical wiring in the building. It is possible that the high current will cause a breakdown in both the insulation on the wiring and the insulation provided by the air, causing an electrical arc to form between the wire and a nearby grounded object. (This is called a "side-flash".) A follow-on current from the electrical circuit would then sustain the arc and could continue for many seconds or even minutes, long after the lightning strike is gone. Combustible material in the immediate vicinity could then be ignited. Although arcing is more likely with the larger-current strikes, any magnitude of strike must be considered. This type of fire may thus be considered *unlikely* for non-HPR facilities without functional lightning protection systems.

5. A lightning-induced spark in the building could ignite volatile gases, such as from rags damp with cleaning fluids. This could occur with a lightning strike of any magnitude current. This type of fire may thus be considered *unlikely* for non-HPR facilities without functional lightning protection systems.

Damage to electronic components from lightning strikes can generally be ignored for safety analyses, as such damage is usually not associated with the release of radioactive or chemically hazardous materials.

From this information the analyst can determine the potential impact of lightning strikes on hazardous materials. The methodology to analyze lightning accidents is to:

1. Define the scenario;
2. Estimate the facility damage from the lightning strike and damage to facility support systems;
3. Identify materials and appropriate MARs and DRs; and,
4. Calculate the consequences for this event.

4.6.7 VOLCANIC ERUPTION EVENTS

Volcanic eruption events can pose a number of hazards to facilities such as ashfall (i.e., tephra), lava flows, ballistic projections, pyroclastic flows, mudflows, low-level seismic activity, ground deformation, tsunami, atmospheric effects, and emission of gasses that can result in acid rains. For existing DOE sites, the primary hazards are from volcanic ashfall. Designing facilities to withstand any other volcanic hazard is not feasible, and such hazards should be mitigated by siting facilities far enough from active volcanoes to eliminate these hazards.

Volcanic eruptions may pose hazards to select DOE sites in the western United States. Volcanic hazards shall be assessed at DOE sites and facilities lying within 400 kilometers of a volcanic center that erupted within the geologic Quaternary Period (i.e., 2.6 million years before present).

The two main issues with ashfall are: (1) the potential clogging of ventilation systems; and, (2) extreme rainfall. Chapter 8 of DOE-STD-1020-2012 and the DOE-HDBK-xxxx-2016 provide additional information about volcanic eruption events.

The accident analyses for the volcanic eruption events are performed in accordance with DOE-STD-3009-2014 and DOE-STD-1189-2008 based on the unmitigated consequences of release of the radiological and/or toxic chemical materials contained in the facility. As stated above, the results of the accident analyses determine the Volcanic Design Category (VDC) for the facility SSCs.

For volcanic eruptions, the facility structure can usually be considered to protect the systems and components inside the facility structure with the exception of the potential clogging of ventilation systems from ashfall which have openings to the outside of the facility structure. The facility structure's failure should be considered in determining the unmitigated consequences of the release of the hazardous material in the facility.

SSCs located outside of the facility structure could be susceptible to the volcanic ashfall and potential extreme rainfall. The failure of these SSCs should also be considered in the accident and consequence analyses.

To analyze the volcanic ashfall events, the analyst should:

1. Define the scenarios;
2. Identity the type of material involved and appropriate MAR and DRs;
3. Determine the unmitigated consequences;
4. Determine the SSCs which will be used to mitigate the consequences; and,
5. Define the VDC for the SSCs that mitigate the consequences.

4.6.8 WILDLAND FIRES

Wildland or range fires present an external exposure to site facilities, and as such, their potential severity needs to be evaluated. The potential severity of a wildland fire may be assessed through an analysis of the chief factors that contribute to its growth and spread. These factors include the characterization of the fuel available, the terrain, and environmental conditions. The damage potential from a wildland fire is dependent on factors such as including the construction of potential target structures, spatial separation distances, existing automatic fire suppression, and the effectiveness of the responding fire fighters. A wildland fire in the site buffer zone may threaten the structural integrity (i.e. MAR confinement capabilities) of site facilities located in the zone, as well as facilities located in the site's industrial area (typically areas of extremely limited vegetation). The fire may spread by flame or radiative heat from building-to-building, or it may be spread to various building roofs by flying brands.

The methodology to analyze a wildland fire is to:

1. Define the bounding scenario.
2. Identify the type of material involved and appropriate damage ratios.
3. Determine the consequences.
4. Determine fire code or other NPH design criteria for the SSCs needed to prevent or mitigate the event.

Additional guidance for the evaluation of wildland fires is provided in Section B.3 of Appendix B.

4.7 EXTERNAL MAN MADE EVENTS

External events can cause a breach in the structure of a facility. The following events are typically evaluated for DSA accident analysis.

4.7.1 AIRCRAFT CRASHES

The analysis of aircraft crash impact involves the following steps.

1. Screening Analysis (based upon MAR, Frequency, and Consequences)
2. Define the scenario.
3. Identify the type of material involved and appropriate damage ratios.

4.7.1.1 SCREENING ANALYSIS

Guidance and criteria for evaluating airplane crashes is given in DOE-STD-3014-2006. The assessment is broken into three phases: 1) determination if there is enough hazardous material in the facility to pose a threat to the public or workers; 2) determination of the estimated probability per year (i.e., frequency) of an aircraft crash into a facility with hazardous materials; and 3) determination if an aircraft crash into the facility would penetrate to the location of the hazardous materials and release them into the atmosphere. If the relevant determination in any of these three phases falls below screening guidelines, the threat of an aircraft crash is considered insignificant for that facility.

For phase one, the screening guidelines are based on the assumption of the total release into the atmosphere of *all* the hazardous material in the facility from an aircraft crash. The screening criteria for the public, for example, are a radiological dose to the MOI of less than 25-rem TED and a toxicological exposure of less than PAC level 2 (PAC-2). Similar criteria apply to the worker. If the amount of hazardous material is insufficient to reach these levels, an aircraft crash into the facility is considered insignificant and phases two and three need not be evaluated.

For phase two, the screening criterion is a crash frequency of less than one crash per million years into the facility. Below this frequency, aircraft crashes are considered insignificant and phase three need not be evaluated.

For phase three, the screening criteria deal with the robustness of the facility. If an aircraft or any of its parts could not penetrate to the location of the hazardous material, an aircraft crash is considered insignificant for that facility.

Refer to DOE-STD-3014-2006 for details on performing these analyses.

Based on experience with applying that standard at multiple DOE sites, additional discussions and guidance follow:

1. Crash probabilities are estimated separately for airport operations (take-offs and landings) from nearby airports and from overflights from more distant airports and are then summed. A variety of aircraft types regularly operate near DOE sites. These include general aviation, commercial, and military. There are typically no special restrictions in place for the air space

around and above a DOE site, although sectional charts may carry an advisory relative to flights below a certain altitude, such as 1,000 feet. Overflights occur occasionally along predefined navigational pathways (Airways). Helicopter operations should also be considered, such as from hospital "Flight-For-Life" and spraying operations. Site-supervised overflights may also be performed by rotary-wing and fixed-wing aircraft for photographic and other purposes. In addition, a nearby airport may host air shows featuring military aircraft conducting displays and acrobatic activities. Small aircraft (those that weigh less than 12,500 pounds) operating from nearby airports are major contributors to the numbers of aircraft in the vicinity of a DOE site.

2. Although a pilot would be expected to attempt a minimal-impact landing, data show that the pilot has no control in approximately 59% of accidents and only limited control 31% of them (Cooper and Gillen, 1993). An aircraft-fuel fire may also accompany this accident. The estimation of the probability of an aircraft accident involving a site facility is based on the air traffic associated with the nearby airports and overflights, and the aircraft crash rate. The aircraft accident rate from airport operations is estimated as the product of the number of flights and the aircraft accident rate per square mile for airport operations (Boonin, 1974; DOE-STD-3014-2006). These data provide accident probabilities for impact locations as a function of distance from an airport. The aircraft crash rate from general aviation overflights is also significant and needs to be considered.

3. For fixed-wing aircraft, the estimated annual aircraft crash frequency from airport operations is calculated from aircraft crash rate for each flight phase (take-offs, landings, and in-flights), aircraft category (e.g., general aviation or commercial), flight source, and effective area of facility, including physical footprint, skid-in area, and shadow. The values of estimated number of site-specific airport operations, for each aircraft category and flight source, are found in airport operations data (http://www.airnav.com/airports/).

4. The crash rates from general aviation, commercial, and military *overflights* are provided in Appendix B of DOE-STD-3014-96 for each DOE site, as well as the maximum, minimum, and average rates for continental United States. The rates for a given site are added to the rate determined from operations at nearby airports to get the total rate. For general aviation, it was found that the overflight crash data may not be accurate for a given DOE site, as the database was limited by the paucity of crash data available when DOE-STD-3014-1996 was prepared. It would be appropriate for the safety analyst to do a reanalysis for a given DOE site. The National Transportation Safety Board (NTSB) datatbase should be consulted to determine the total number of crashes within a certain distance from the site. The area chosen must be small enough to be representative of the Site, but large enough to include a sufficient number of accidents so that meaningful statistics can be derived. For sites in more heavily populated areas, it could be as much as 50 miles to obtain an adequate data sample.

5. Another parameter to calculate the likelihood of an aircraft cra*shing into* a facility is the aircraft crash location conditional probability at the facility location (x,y) relative to the runway. The coordinates x and y are relative to the runway, with the origin being at the center of the runway, positive x in the direction of takeoff or landing and positive y in the direction 90° counterclockwise from positive x (i.e., to the left). The bearing of the airport from the facility (θ) from geographic north, the bearing of the runway (φ) from magnetic north, and the distance (R) between the facility and runway are needed to calculate the (x,y) coordinates of the facility from the center of the runway.

   The coordinates of a facility relative to the runway are thus

$$x = -R\cos(\theta - \varphi)$$
$$y = R\sin(\theta - \varphi)$$

The calculation of R is based on the differences in latitude and longitude of the facility and airport.

Runway labels are expressed as azimuth degrees/10. Thus, runway 22 is has a bearing of 220° and runway 4 has a bearing of 40°. The runways 4 and 22 are physically the same but differ in designation depending on the direction of motion of the aircraft, with 4 being to the northeast and 22 to the southwest. Runways may also have a left/right (L/R) designation if there are two runways side-by-side with the same orientation; sometimes, C is used for Central. The true runway bearing may differ slightly from its designation. For example, runway 22 might have a bearing anywhere between 215° and 225° from magnetic north. The difference between geographic north and magnetic north, the magnetic declination, needs to be considered and if it is smaller than the uncertainty in the runway bearing it may be ignored. The magnetic declination can be found at National Oceanic and Atmospheric Administration National Geophysical Data Center website http://www.ngdc.noaa.gov/ngdc.html and clicking on Magnetic Field Calculators.

6. The values of effective area are dependent on the dimensions of the facility and aircraft type. As the effective area depends on the side of the building the aircraft crashes into, it should be evaluated for all reasonable approach directions and the largest value used.

7. For buildings that are partially protected by other buildings or a hillside, the analyst should use the building dimensions appropriate for the direction of approach of the aircraft to the exposed wall(s). To be conservative, assume that the aircraft will approach from the side that gives the largest unprotected target area.

8. Helicopter crashes are treated differently from fixed-wing aircraft crashes. The helicopter crash frequency into a facility is given by $F_H = N_H P_H A_H (2/L_H)$, where N_H is the number of helicopter local overflights per year at the site, P_H is the probability of a helicopter crash (2.5E-5 per operation), A_H is the facility footprint area, and L_H is the average length of the flight path over the site. The term $2/L_H$ arises from the conservative assumption that the helicopter crash takes place within 0.25 miles from the centerline of the flight path. This gives a total area in which the helicopter crashes of 0.5 miles wide and L_H miles long, for a conditional probability of $1/(0.5L_H) = 2/L_H$ per square mile. If the value of L_H is not available, it can be estimated as the distance to the nearest heliport.

4.7.1.2 AIRCRAFT CRASH DAMAGE ASSESSMENT

If an aircraft crashes into the portion of a facility housing radioactive or other hazardous materials, that material could be released by a fire (Section 4.2), explosion (Section 4.3), and/or by loss of containment (Section 4.4).

4.7.2 VEHICLE CRASHES

Two types of vehicle crashes need to be considered. (1) If a vehicle crashes into a facility, material in that facility could be released. (2) Transportation accidents can release radioactive and other hazardous materials from the vehicle transporting these materials.

4.7.2.1 VEHICLE CRASH INTO FACILITY

The accident analysis methodology for external vehicle crash into a facility is:

1. Identify the scenario.
2. Identify whether a fire initiator is present; (Generally, one is present if the accident involves a motor vehicle).
3. Identify the type and quantity of materials present.

4.7.2.1.1 EXTERNAL VEHICLE CRASH EVENT DESCRIPTION AND ANALYSIS

If a vehicle crashes into the portion of a facility housing radioactive or other hazardous materials, that material could be released by a fire (Section 4.2), explosion (Section 4.3), and/or by loss of containment (Section 4.4). The analyst needs to determine the likelihood of such an accident based on the location of the MAR in the facility relative to the route the vehicle must take to impact that portion of the facility.

4.7.2.1.2 EXTERNAL VEHICLE CRASH DAMAGE ASSESSMENT

The amount of fuel in the vehicle (assume the maximum), any combustibles it contains, and the facility combustibles at the crash site needs to be estimated. Then, following the guidance in Sections 4.2, 4.3, and 4.4, the source term can be estimated.

4.7.2.2 ONSITE TRANSPORTATION ACCIDENT

Transportation of radioactive and hazardous materials presents special hazards to operations and to personnel at the site due to the close proximity of these vehicles to facilities and the reduced level of containment of the materials while outside buildings. These types of materials include special nuclear material (SNM), residues, TRU waste, TRU mixed waste, low-level waste, low-level mixed waste, RCRA-regulated waste, Toxic Substances Control Act (TSCA) waste, samples, contaminated soil, incoming bulk shipments of fuels, acids, bases, miscellaneous chemicals, compressed gases, and laboratory reagents.

The accident analysis methodology for transportation accidents is:

1. Identify the scenario.
2. Identify whether a fire initiator is present (generally, one is present if the accident involves a motor vehicle).
3. Identify the type and quantity of materials present.
4. Calculate the consequences of the accident.

4.7.2.2.1 ONSITE TRANSPORTATION EVENT DESCRIPTION AND ANALYSIS

The analyst needs to examine shipping records to determine the frequency, type of material, and quantity of shipping, both on-site and to/from off-site. The shipment of bulk fuels and chemicals also needs to be quantified. This would include the type of material, the total amount shipped, the average delivery size, and which facilities are involved. Each site should have an on-site transportation manual that lists the packaging configurations currently approved for on-site and off-site use. For example, no package may be used for Pu or uranium unless it has received a criticality safety evaluation and been found critically safe for its intended use. It is not uncommon for transportation accidents to occur at a site. Most of these accidents involving radioactive material transfer would not be severe, and there could be minor releases. Loading and unloading accidents are the most common and could involve forklifts.

In estimating the MAR in a transportation accident, the maximum number of packages that can fit on a truck should be assumed present, unless a specific justification is stated for a different number. An example of truck capacities is shown in Table 4-9, which provides the capacities of transport vehicles for a full load of each type of package that can be hauled. Different size vehicles used at a particular DOE site for transport of containers should be evaluated. Because of the requirement to keep radiation exposure levels in the truck cab below 5-mrem/hr, these capacities are conservative for SNM and waste drums. If analysis with these capacities provides unacceptable consequences, then the truck inventory should be limited by administrative controls.

For a single drum accident, the maximum amount of material allowed by criticality limits should be assumed to be in the drum. For large numbers of drums, where the actual inventories may be vastly different from the allowed inventories, it may be acceptable to use an average inventory such as that estimated for low-level waste, however, the importance of this assumption may affect the need for an administrative control to preserve this assumption

Table 4-9. Example of Transport Vehicle Package Capacities.

Transport	Truck Bed Size	SNM and Residues		
		Number of 10-Gallon Drums	Number of 30-Gallon Drums	Number of 55-Gallon Drums
Enclosed Metal Van	7’ 7” × 12’	54	28	18
Enclosed Metal Van	7’ 7” × 13’ 9”	66	32	21
Dump Truck	7’ 6” × 15’ 10”	72	36	24
Box Van	17’ 8” × 15’ 11”	168	90	72
		LLW and Hazardous Waste		

Transport	Truck Bed Size	SNM and Residues		
		Number of 10-Gallon Drums	Number of 30-Gallon Drums	Number of 55-Gallon Drums
		Number of Half-Size Crates	Number of Full-Size Crates	Number of 55-Gallon Drums
Flat Bed Trailer (for on-site transfers)	8’ × 55’	10 (weight limited)	12 (weight limited)	112
Tractor Trailer Van (for off-site shipment)	8’ 6” × 53’ or two 25’ long in tandem	10 (weight limited)	12 (weight limited)	208

The material that could be released by crash should be determined depending upon the result of the event, i.e., whether it results in a fire (see Section 4.2), explosion (see Section 4.3), and/or by a spill/crushing/loss of containment (see Section 4.4).

4.7.3 STATION BLACKOUT

The accident analysis methodology for station blackout is:

1. Identify the scenario;
2. Identify the type and quantity of materials present; and
3. Calculate the consequences of the accident.

4.7.3.1 STATION BLACKOUT EVENT DESCRIPTION

The Station Blackout scenario results from a loss of AC power within a facility, resulting in loss of all forced ventilation. Direct current power is not assumed available. At the onset, key building support systems such as ventilation system and GB inerting are lost. When the ventilation system loses power, the ventilation fans coast-down and there may be a slight pressure gradient that favors airflow from the GB out into the module. Such air reversal is postulated to draw some radioactive material from the GB into the module. In addition, with the loss of inerting atmosphere within the GBs, a small pyrophoric fire could also be initiated within a GB.

For the Station Blackout scenario, resuspension of holdup material and exposed inventories in GBs should be evaluated. The inventory of holdup material should include quantities in the facility GBs, and ventilation ducting. A loss of power is also a primary initiator for loss of GB inerting which, while it occurs slowly, increases the probability of a pyrophoric fire involving vulnerable material that may be left unpacked. If a pyrophoric fire was considered credible in the fire analysis, then a pyrophoric fire should be considered in the Station Blackout scenario as well. The MAR for the pyrophoric fire during a Station Blackout scenario should be the same as the MAR for the pyrophoric fire from the fire analysis.

If a Station Blackout can initiate a release of hazardous material, then these scenarios and associated controls need to be specified as a specific DBA/EBA.

5 SOURCE TERM ANALYSIS

5.1 INTRODUCTION

This chapter addresses development of source terms for accident analysis. The source term is the amount of hazardous material released from a given confinement volume under the stress posed by a hypothetical phenomenological event.

This chapter covers application of the five-factor formula presented in Figure 5-1 below: MAR, damage ratio (DR), ARF, RFs and leakpath factor (LPF), as described in the DOE-HDBK-3010-94. These parameters are evaluated in terms of the stresses imposed by internal events, external events, and natural phenomena.

Examples of the type of thought processes, bounding assumptions, and overall methods used in parameter determination are also provided.

5.2 CALCULATING SOURCE TERMS

The amount of hazardous material released as a result of accident-imposed stresses is typically evaluated by a prescribed formula that considers the influence of those five factors. Figure 5–1 displays those factors and their relationships. The basic concept is as follows:

MAR × DR × ARF = Initial Source Term (IST)

IST or IRST × LPF = Building Source Term (BST)

and

IST x RF = IST that is respirable

IST (respirable) × LPF = BST that is respirable[16]

The material potentially available to be affected is the MAR. The DR represents that fraction of available material actually affected by the accident stresses. The ARF represents the fraction of material actually affected that is driven airborne, either as a gas or a respirable aerosol. Together, these three factors define the amount of material in the air at the immediate point of release, or the IST. The airborne pathway is normally the exposure mechanism evaluated as it is the principle means by which exposures at a distance from the point of release can occur. Releases to large bodies of waters are a special case where the IST would reduce to simply the MAR × DR, with the DR being expressed as a total fraction or material released or a leakage rate.

[16] The “BST” that represents the MAR × DR × ARF × RF × LPF has been called the “five-factor formula” and is generally presented as the “Source Term (ST)” when describing the input to the radiological consequence analysis for inhalation dose calculations.

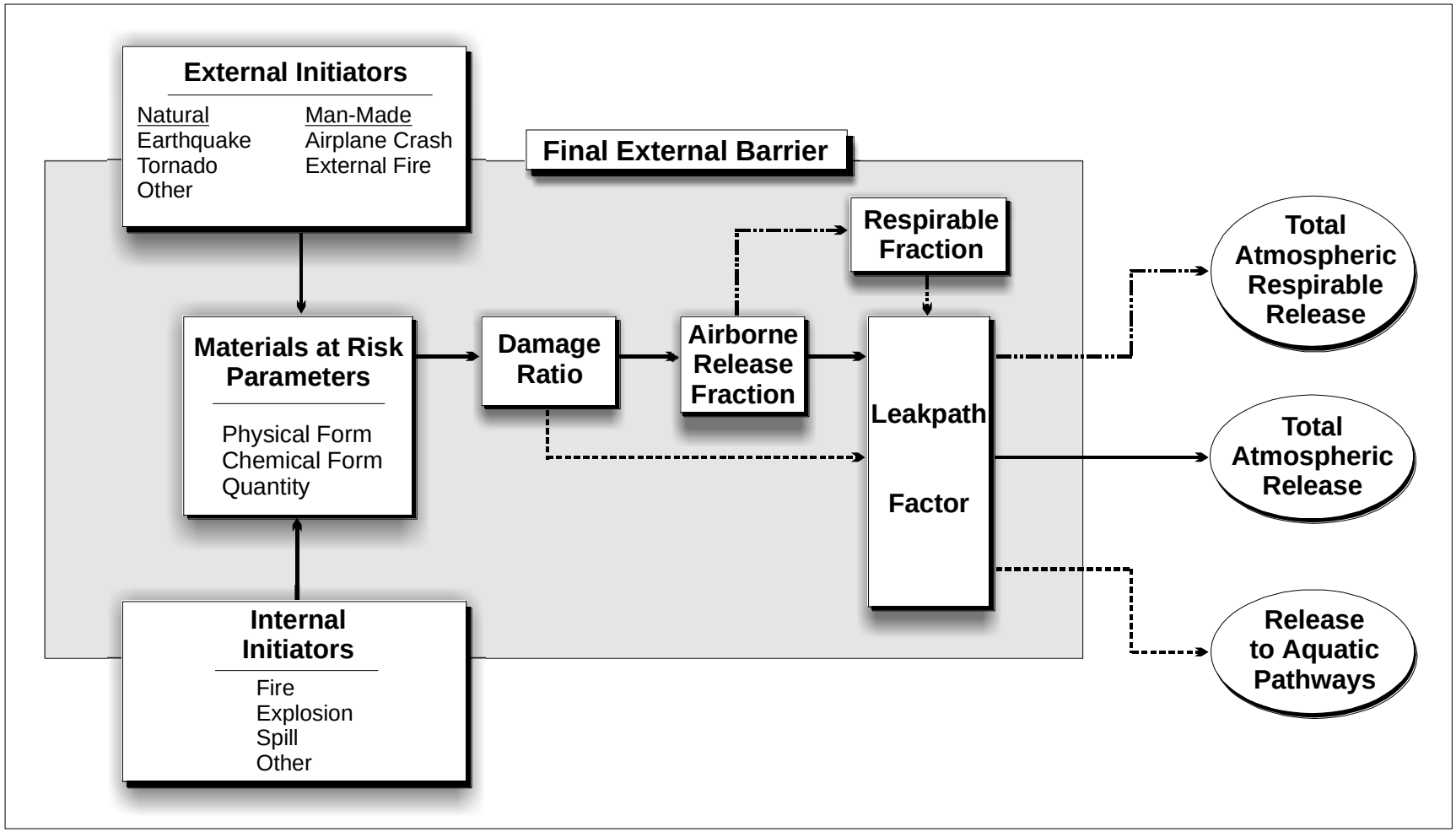

Figure 5-1. Five Factors Formula.

The RF identifies what fraction of the airborne aerosol can be inhaled and retained in the body. The responsible portion of the IST is of major interest for nuclear material handling operations as, with the exception of MAR such as tritium gas, criticality fission products, or high energy gamma sources, most materials of concern (e.g., plutonium, uranium) are alpha emitting radionuclides. These present no significant dose hazard outside the body. For gases, of course, the IST and the IST respirable amount are the same.

An LPF accounts for source term depletion due to filtration or deposition as the source term migrates through various layers of confinement. By far the most common application of LPF is HEPA filtration in exhaust ventilation. Applying all relevant LPFs yields the amount of material released to the environment, sometimes called the BST as most handling operations occur inside fixed facilities. The LPF is of interest primarily for mitigated analysis, and is not considered for unmitigated analysis absent unusual circumstance.

5.2.1 MATERIAL AT RISK (MAR)

5.2.1.1 OVERVIEW OF REQUIREMENTS, GUIDANCE, AND PRACTICES FOR IDENTIFYING MAR

DOE-STD-3009-2014 provides the following direction regarding MAR:

> *"The MAR is the bounding quantity of radioactive material that is available to be acted upon by a given physical stress from a postulated accident. The MAR may be the total inventory in a facility or a portion of this inventory in one location or operation, depending on the event. MAR values used in hazard and accident analysis shall be consistent with the values noted in hazard identification/evaluation, and shall be bounding with respect to each accident being evaluated."*

The concept is considered equally applicable to hazardous chemicals.

The MAR value assigned should be consistent with the DSA hazard identification[17] documented for a given facility or operation. That is, the DSA hazard identification used some basis to determine the maximum hazardous material accumulation foreseeable. The MAR should use that same basis. If it does not, absent some compelling explanation, the basis for either the hazard identification or the MAR designation, or both, becomes suspect. Therefore, if some compelling explanation for a discrepancy does exist, it is preferable to modify the DSA hazard identification to incorporate that explanation.

Specifying the amount of a given material foreseeable is typically based on physical possibility, procedural or other administrative limits, or sampling/historical data. Physical possibility is most often used as a basis with regard to fixed volumes, such as storage vessels. In these cases, the maximum amount of material present can be precisely specified.

Administrative limits dominate the assignment of MAR values for radioactive material handling in glovebox-type environments. These environments are constructed to allow operations within the confinement, as opposed to serving as simple holding volumes. Normal practice is to assess specific

[17] Note that the DSA hazard identification values are is not necessarily the same as the initial data generated in the hazard identification activity itself. As noted in Section 2.2, Hazard Identification and Characterization, the DSA hazard identification may identify bounding MAR values as opposed to maintaining a plethora of inventory limits.

workstations, glovebox vessels, storage containers, etc, in terms of batch sizes, process parameters, and criticality or other procedural limits. It is noted, however, that criticality limits are sometimes set at elevated values in comparison to actual operating quantities in order to minimize the chance of a violation. Where this is the case, the MAR may be assigned a lower value as long as that value is captured in procedural limits, which assumptions are protected as initial conditions as discussed in Chapter 2.

Statistical sampling or historical data are primarily used for waste-handling and environmental cleanup activities. While some waste-handling operations will have physical upper limits for a given storage vessel such as a drum, much of the radioactive material of concern is mixed with debris, liquid or dirt and is present in very dilute concentrations. To assume a vessel is filled to capacity with concentrated material in such cases is a gross exaggeration of reality. Likewise, the condition of residual material in cleanup efforts may not support precise specification of the quantities involved. A theoretical reconstruction based on historical data, measurement, sampling, or some combination of these is required. This is consistent with the statistical treatment of TRU waste allowed in DOE-STD-5506-2007, as discussed later in this chapter.

Sometimes for simplification of accident analysis calculations it is beneficial to introduce the concept of surrogate compositions. For example, the concept can be used to establish a common inventory or tracking basis for a dose calculation. It can provide a process for accepting new material while remaining within the bounds of the accident analyses, thus allowing operational flexibility while complying with the safety basis and source strength administrative control limits. See Section 6.2.2.3, Plutonium Equivalent Curies (PE-Ci), for a further discussion of dose equivalent concept.

It is not appropriate to use this PE-Ci methodology for criticality safety evaluations.

Sealed radioactive sources that meet any of the following testing specifications may be excluded from summation of a facility's radioactive inventory as part of the initial facility hazard categorization: Department of Transportation (DOT) Special Form criteria per 49 CFR 173.469; Nuclear Regulatory Commission (NRC) Special Form criteria 10 CFR 71.75; ANSI N43.6/ISO 2919 Annex E Special Form criteria; or ANSI N43.6/ISO 2919 Class 4, Class 5 or Class 6 (or Class X equivalent) performance criteria for temperature, impact, and puncture.

However, if an accident environment involving sealed sources exceed in severity the relevant test criterion listed above, the contents of the sealed source are included in the accident MAR and the facility final hazard categorization.

5.2.1.2 EXAMPLES FOR IDENTIFYING MAR

Figure 5–2 offers a simplified representation of a nuclear materials handling facility modeled off the example plutonium recovery facility in DOE-HDBK-3010-94. It consists of three glovebox processing rooms: a metal dissolution line, an ion exchange and precipitation room containing two gloveboxes, and a fuel fabrication room containing four gloveboxes. There are also two gloveboxes in a laboratory, one for handling solid samples and the other for handling liquids. Waste is stored in 55-gallon drums in a waste handling room. Finally, there are three storage vessels outside the facility: a chlorine gas supply to the laboratory, and sulfamic and nitric acid storage tanks. A MAR is developed for each of these operations.

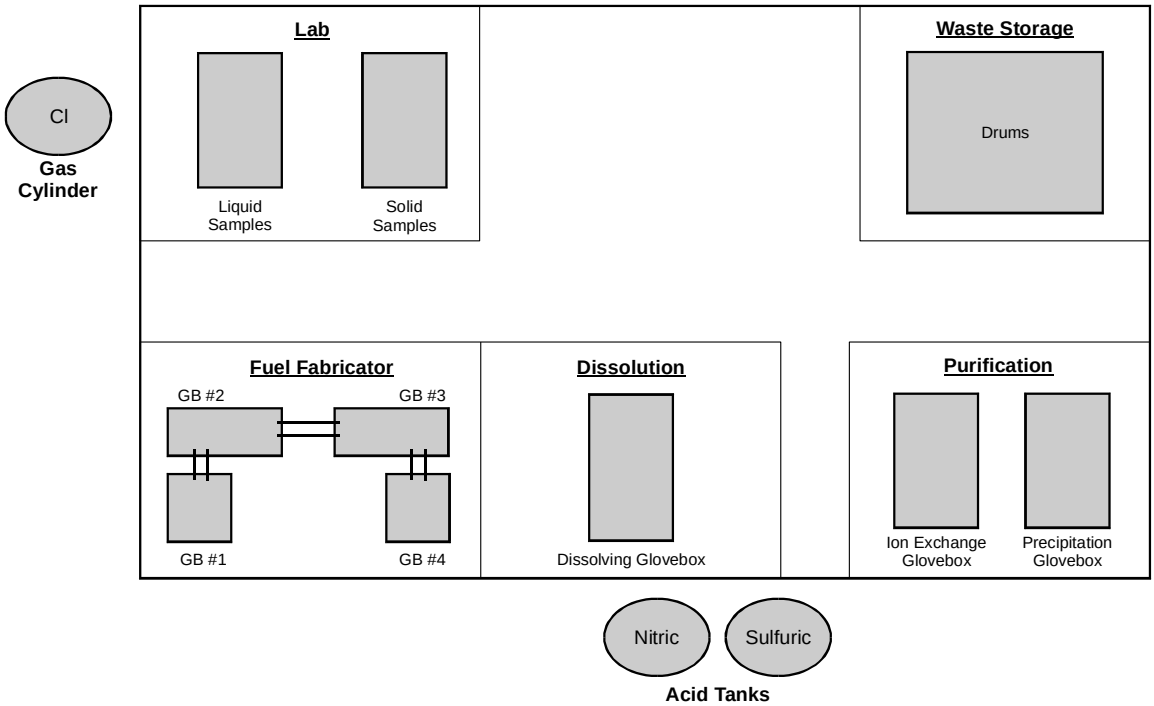

Figure 5-2. Example Facility.

Note that the following discussion is for the sake of example only, and none of the fictitious quantities cited are intended to represent actual operations in the weapons complex.

MAR in External Storage Tanks

Simple physical possibility, with some reference to procedural limits, is used to identify the MAR for these operations. Suppose the chlorine source is a standard vendor-supplied compressed gas cylinder containing 30 pounds of chlorine. As the cylinder volume is fixed and its pressure is monitored by the supply manifold, it is not reasonable to presume a quantity of material greater than 30 pounds based on the unlikely possibility of the vendor overcharging the cylinder. Likewise, if the external acid supply tanks are sized to hold 3,000 gallons, that is maximum volume potentially present. Procedural limits factor into defining the operating concentrations desired. If 32 percent by weight nitric acid and 15 percent sulfamic acid are what is supplied, these would be the values used to define density, volatility, etc.

Chlorine: 30 pounds in gaseous form

Nitric Acid: $3{,}000\text{gal} \times 1\text{ft}^3/7.48\text{gal} \times 74\text{lb/ft}^3 = 30{,}000$ lb of solution

$30{,}000$ lb of solution $\times\ 0.32 = 9{,}600$ lb of acid

Sulfamic Acid: $3{,}000\text{gal} \times 1\text{ft}^3/7.48\text{gal} \times 75\text{lb/ft}^3 = 30{,}000$ lb of solution

$30{,}000$ lb of solution $\times\ 0.15 = 4{,}500$ lb of acid

MAR for Dissolution Glovebox

The metal dissolution glovebox holds a small spray chamber, a 30-liter acid storage tank, a heat exchanger, a small pump, and various piping and valves. Single plutonium metal shapes are then placed in the spray chamber and dissolved by a heated acid spray recirculated from the slab tank via the following reaction:

$$Pu + 3NH_2SO_3H \rightarrow Pu^{+3} + 3NH_2SO_3^{-1} + 1.5H_2$$

In this case, the glovebox volume is capable of holding a great deal more material than practical operating considerations will allow. Therefore, the MAR is derived from administrative limits.

Plutonium

Suppose criticality calculations have determined that the criticality limit for the acid storage tank is 100 g of plutonium per liter. A volume of 30 liters would then allow 3,000 g of plutonium. But further suppose that that the actual pieces to be dissolved each individually contain a maximum plutonium inventory of 750 g. The critical discriminator would then be how the process is operated. If four 750 g pieces are allowed to be dissolved before the dissolving solution is sent out of the box, the bounding MAR values would be as follows:

3,000 grams in liquid form, or

750 grams in solid form, or

whatever combination of both forms could result in the bounding radiological consequences.

On the other hand, if only one item can be dissolved at a time, after which the acid tank solution is sent out of the box, then 750 g of plutonium could represent a reasonable bound. Or the bound could be 1,000 grams if this limit is being normalized with the limits of other operations to provide for TSR consistency. Further, the limit might even be 2,000 grams for the entire glovebox to normalize glovebox TSR limits. There are multiple potential answers depending on how the operation is run and how material limits are apportioned.

Potential administrative burdens on facility management should be considered as well. Suppose the limit had been set at 750 g. If a campaign of unusual shapes ranging in quantity up to 1,000 g becomes necessary, and there is no way to split the shapes into two pieces a facility might again choose to assign a larger MAR limit for flexibility. The key point is that the limit allowed is the amount analyzed.

Flexibility is allowed within reasonable bounds. One such bound would be the criticality limits. DOE would not allow a MAR greater than these limits, as the authorization basis would then implicitly authorize their violation. Subtler judgments could come into play if criticality is not limiting, as can be the case with solid storage, particularly of uranium.

MAR from Fuel Fabrication

This process takes as feedstock purified oxide powders from the ion exchange and precipitation process which takes the plutonium-bearing dissolution product. Fuel fabrication consists of four gloveboxes containing a variety of milling, blending, sintering, and fuel matrix formation stations. Assume there are 13 distinct operating stations with operating limits as follows:

Operating Limit	Number of Stations
1,000 grams	4
2,000 grams	3
3,000 grams	6

These limits yield a cumulative quantity of 28 kg of plutonium oxide for the overall room. The way in which the process is operated, however, could affect that conclusion. Suppose the process is a semi-batch operation run in campaigns. Three-thousand grams (the feed of four dissolving operations) may be entered into glovebox #1, and 3,000 more grams entered when the first batch has progressed to glovebox #3. After the completion of this second batch, the process is then shut down for accountability cleanup. If that is the case, then the overall MAR figure for the fabrication room could decreases to 6 kg of plutonium oxide. Again, the MAR assumed in accident analysis is a function of how facility management chooses to control the operation, and the MAR assumptions may require protection and coverage in the TSRs.

Note that to the degree individual accidents are sufficiently localized so as to affect only a subset of stations, the scenario-specific MAR might also be only a fraction of the overall total. Given the nature of the operation, there may also be a point in processing beyond which the material is no longer at risk from phenomena threatening the entire room (e.g., after incorporation into a ceramic matrix). The accident analysis needs to consider station-specific form in order to fully assess vulnerability.

MAR for Waste Storage

The waste storage area provides temporary storage capacity for up to thirty (30) 55-gallon drums of TRU waste. The drum limit for disposal is 80 curies PE-Ci. Based the fact that no drums from this facility have ever approached that level, the facility has an internal restriciton of 10 PE-Ci/drum, but managed as 300 PE-Ci as a facility limit. The historical database for the facility, which covers a period of 15 years and includes a statistically significant amount of data, indicates the 95th percentile drum loading is 3.0 PE-Ci, the 50th percentile loading is 0.2 PE-Ci, and the average loading is 0.4 PE-Ci.

Based on a maximum capacity of 30 drums, the MAR can range from a minimum of 6 PE-Ci (based on 50th percentile loading) to a maximum of 2,400 PE-Ci (based on disposal limit), while the average loading is about 12 PE-Ci for the entire facility. That considerable range requires common sense parsing. At a minimum, the internal limit of 10 PE-Ci/drum or 300 PE-Ci for the facility is an acceptable bound. This is also a case where the use of statistical sampling or historical data should be considered. Even the 95th percentile drum loading is a factor of three less than the local facility limit, and the average loading is a factor of 25 less. Table 4.3.2-1, Bounding MAR Limits for TRU Waste Operations 4, of the DOE-STD-5506-2007 provides a statistical algorithm on how to address multiple drum accidents.

The use of statistical sampling and historical data is common in cases of old waste storage or environmental restoration where detailed NDA records do not exist. One such example is the case at Rocky Flats where plutonium residues had built up in ventilation ducting over many years. Prior to cleaning out this material, selected samples were taken to characterize the range of physical forms and chemical composition. This data was augmented by NDA measurements of radiation levels along the length of the ductwork to arrive at workable estimates of material holdup quantities. It is important in such cases to be conservative, but again such conservatism should not try to protect itself from criticism by estimating unrealistically large quantities potentially that obviously skew the assessment process.

5.2.2 DAMAGE RATIO (DR)

5.2.2.1 OVERVIEW OF REQUIREMENTS, GUIDANCE, AND PRACTICES FOR DETERMINING DR

The DR is the fraction of material that is actually affected by the accident-generating conditions (DOE-HDBK-3010-94). DOE-HDBK-3010-94 notes that some degree of ambiguity can result from overlapping definitions of MAR and DR. A given DSA should use one consistent definition throughout. A DR of 1.0 is used unless there is an applicable standard or technical basis for a different value. For example, DOE-STD-5506-2007 contains specific DRs (and associated MAR guidance) that may be used in TRU waste operations.

There is an intrinsic interdependence between the definitions of MAR and DR. In simplest terms, the overall area impacted by an event, as well as the magnitude of any energy release, determines what material is impacted. But that can also be thought of as determining what materials are available to be acted upon.

This distinction is made clear by considering two cases. The first is an explosion that affects only one room in a large facility and does not have the capacity to generate a large fire. Most analyses will focus only on that one room. They will not typically even consider material in other rooms, as by definition such material is not at risk, and thus not part of the MAR. A purist argument can point out, however, that the material in other rooms is MAR with a DR of zero for that scenario.

The second case is a seismic event that shakes the entire facility and topples various weak gloveboxes throughout the facility. In this case, analyses typically identify material in every room as MAR, specifying DRs over the range of zero to one for each specific case. Because the event affects the entire facility, it is deemed necessary to demonstrate that every potential source of release has been considered. Or, in simpler terms, the practical limits of what could be MAR are not self-evident from the scenario definition itself.

This relationship between MAR and DR may seem trivial. There have, however, been multiple analyses that have stumbled over it. MAR has been defined imprecisely enough that DRs for a given form were credited when that form had already been stricken from the MAR, and DRs greater than zero were applied to material not ultimately at risk. In the former case, the DR is effectively credited twice, yielding a nonconservative source term; in the latter, it is effectively omitted so that the source term is excessively conservative. The relationship between MAR and DR is pointed out to emphasize the need for precise definition of each with reference to the other. Either unaffected material is not considered MAR, or it is and assigned a DR of zero. Likewise, material with a DR greater than zero should be identified as MAR. The simplest convention for avoiding confusion is to identify all material within the structural subdivision

affected by the accident (e.g., glovebox, room, wing) as MAR. DR values of zero are then assigned for material not impacted in any significant fashion.

DR values are based on the response of MAR form and available shielding to the stress imposed, as attenuated by any distances involved. In many cases, the nature of the stress-to-distance, stress-to-shielding, or stress-to-form relationship is simple enough to assign a DR from general engineering knowledge or historical experience. Ion exchange exotherms are a well-understood potential in certain operations, sufficiently so that many have been re-engineered to eliminate or minimize that possibility. If vitrified glass, or even hardened cement, waste is co-located in a room with an ion exchange glovebox, these can be quickly eliminated as MAR significantly impacted by the exotherm for all but the most unusual of circumstances. Likewise, spilling a plutonium nitrate solution from one glovebox is not going to affect material in other gloveboxes.

When the nature of the stress relationship is not so simple, engineering estimates of type and level of stress are performed in conjunction with assessments of structural strength for available shielding and confinement. Seismic assessments determine whether a given glovebox will remain stable or fall over, and whether massive objects in the overhead will impact the glovebox either way. Fire modeling can estimate whether or not temperatures necessary for combustion of bulk metal will occur for an extended period of time. Blast calculations can determine if a steel vessel at a given distance will remain intact. All of this information may be needed to define a DR of zero, one, or any fraction in between.

5.2.2.2 EXAMPLES FOR DETERMINING DR

Examples are provided in the following subsections to illustrate the thought process for determining DRs. These are not bounding default recommendations, and use in a DSA will require appropriate justification in context with the scenario being analyzed.

<u>Determining DR for Fire Event</u>

Pyrophoric Metal fines

The hazard identification states that 100 g of metal fines is the maximum amount of metal contamination anticipated in impure oxide received for processing. The absolute limit is 2,000 g if an entire feed can contains nothing but metal fines, but the maximum anticipated DR is 0.05. The DR for metal fines present is never anticipated to be 1.0, but that value can be assumed for the sake of simplicity. Other batches are not affected by the localized combustion.

<u>Determining DR for Explosion Event</u>

Assume four liquid tanks holding plutonium nitrate solution. The location of the tanks is split, with two each being located on opposite sides of a large room. There is a significant amount of intervening equipment between them.

The tanks are physically sized to hold 200 liters of solution. At a nominal operating concentration of 30 g Pu/l, the tanks could physically hold 6 kg. The operational flow sheet for the process, however, indicates that each batch contains only 1 kg of plutonium. The operating limit specified in procedures is 1.5 kg.

Assume that under certain conditions, any tank can experience a runaway reaction that overpressures the tank to failure. However, each is operated independently, so that a common cause for multiple over-pressurizations simultaneously does not exist. How should the MAR and DR be defined?

The staring MAR would be 1.5 kg Pu per tank. This is the allowable limit, irrespective of the fact that only 1 kg of Pu is expected per tank. If facility management does not desire to analyze 1.5 kg of Pu per tank, the operational limit should be lowered. Facility management may also choose to analyze a higher value, say 2 kg of Pu per tank, for future flexibility. There is no obligation, however, to assume 6 kg of Pu per tank simply because one could physically do that. That conclusion is no different than a glovebox example, where one works with the practical limits established as opposed to calculating how much solid material could physically be crammed into the box at a given density.

So each tank contains 1.5 kg Pu for the DSA analysis. The next question to answer is what happens to that material? The liquid in the tank where the runaway reaction occurs will experience an over-pressurization release phenomena. What happens to the other tanks is a function of two variables: (1) location, and (2) the violence of the original tank failure.

There are two tanks on the same side of the room. If the first tank merely experiences a localized weld failure, the second tank on that side of the room should not be damaged. On the other hand, if the second tanks bursts violently into multiple pieces, and the second tank is directly adjacent, it is reasonable to consider whether the second tank could be punctured. The answer to that question would be determined by mechanical engineering calculations. For example purposes, assume the second tank would be punctured.[18]

The final issue to consider is the two tanks on the opposite side of the room. If the room is large, and the process equipment occupying the floor space between forms a natural barrier, a reasonable assumption is that the remaining two tanks are unaffected. That is an acceptable conclusion for an unmitigated analysis given that no specific preventive or mitigative capability is being credited. The relative locations of the tanks are physical facts, and the process they serve intrinsically requires equipment located on the intervening floor space.

As noted previously, the MAR for each tank is 1.5 kg of plutonium. The associated damage ratios for each release phenomena are:

Tank	**Over-pressurization Release**	**Spill Release**
Ruptured Tank	1.0	1.0
Adjacent Tank	0	1.0
Opposite Tank 1	0	0
Opposite Tank 2	0	0

[18] If the tank would not be punctured, the question arises as to whether that capability constitutes a credited feature. The answer depends on whether intrinsic margin exists or not. If the projectile stress is of sufficiently limited nature that any similar steel vessel can clearly survive, there is no special capability to be preserved. If, however, the vessel in question is uniquely thick for some reason, and that is what allows its survival, then that capability should be noted as a safety (safety class or safety significant) SSC provided its leaking significantly increases consequences.

Alternatively, as previously discussed, the analyst could choose to state that the tanks on the opposite side of the room are not MAR for this particular hazard scenario. Other subtleties could come into play as well. If, for the purposes of example, it is not physically possible to generate a puncture in the adjacent tank at low levels, perhaps only 50 percent of the adjacent tank contents could spill. The spill release DR for that tank might then only be 0.5.

In the mitigated scenario, of course, the damage ratios can change significantly. For example, if one credits a pressure relief system designed to handle the runaway reaction, there may be no release at all. Or there may be a smaller release depending on the ultimate destination of the pressure relief outlet.

A final factor to consider is human error. That is not a player in this scenario as developed, but suppose one was examining the potential for human error to drain one of these tanks in a spill scenario. At only two hundred liters, if there is a plausible way to initiate a spill by erroneous draining, one should assume the entire tank spills. Yes, it might be noticed and the process stopped, but the available volume relative to typical pump capacities can result in emptying the tank relatively quickly. A DR less than 1.0 would thus be inappropriate. On the opposite extreme, assume one is evaluating a legacy liquid waste storage tank holding over two million liters of solution. At some point, the cumulative level of human error required to drain the entire tank can become willfully egregious. There is no requirement to analyze scenarios that become physically ridiculous, so a reasoned basis for the maximum portion of the tank that might be drained is acceptable.

<u>Determining DR for Spill Event: Powder Spill from example 7.3.1 in DOE-HDBK-3010-94:</u> As discussed in that Handbook, the DR for a spill event would be typically be 1.

<u>Liquid Spill from example 7.3.2 DOE-HDBK-3010-94:</u> A spill can occur from a piping or vessel leak due to corrosion, or inadvertent damage from an activity such as maintenance or an unrelated accident. If the leak in a line is small, or a leak in a vessel is above the vessel bottom, not all of the material would be spilled. For the sake of simplicity, a leak large enough and situated so as to allow all of the liquid to drain from confinement is postulated (i.e., DR = 1.0).

<u>Liquid Spray</u>: The use of a centrifugal pump for liquid circulation generates positive pressure. While the pressure is not high in this small process, it is sufficient to produce liquid spray and thus a different release stress than the vacuum transfer systems in other dissolution lines. A pump seal, flange failure, or even a piping leak could cause spray generation. The maximum amount of material available in solution is 1,200 g of plutonium if all of the metal is dissolved. The DR will probably not be 1.0 even if no operator intervention occurs as the pump eventually shuts off from loss of net positive suction head after sufficient liquid is lost. The distinction, however, could be minor; therefore a DR of 1.0 is used for the sake of simplicity in this example.

Determining DR for Exothermic Event

The first key question regarding a damage ratio is how many columns will be affected, and in what way? The initial degradation reaction will start in one of the columns. There are three mechanisms by which other columns can be affected.

First, if the temperature of the liquid flowing from the affected column to the next column in line is sufficiently high, it may initiate a resin exotherm in the next column. Secondly, when the affected column ruptures, historical experience and understanding of the phenomena indicate that at least some of the resin from the damaged column will continue to burn on the glovebox floor.

How much will burn depends on whether the resin is grouped together to maintain local temperature above the autoignition temperature, and on the effectiveness of available means of fire suppression. If a large amount of resin burns, the heat generated may be sufficient to initiate resin exotherm reactions in the undamaged columns. This effect is by no means certain and there are historical incidents where an exotherm in one column was followed by a fire with no subsequent exotherm in adjacent columns. In the Hanford exotherm incident discussed in Section 4.5, Analysis of Chemical Reactions, and in Appendix D, the presence of a significant amount of uncharred resin was reported after the incident. Finally, the other columns may not be undamaged in the initial explosion. They may be shattered by shrapnel from the damaged column, in which case spilled resin may burn, but pressurization of multiple columns is not possible.

Therefore, depending on how many columns are assumed to be affected by a given stress, the first potential factor of the damage ratio is 0.33, 0.67, or 1.0. A second potential factor is, at least for solids, how far the process is into a loading or elution cycle. For example, if only 2,000 g are loaded at the time of an exotherm reaction, the DR is 2,000/6,500 = 0.3. If both potential factors are used, they need to be defined together so that "double-counting" does not occur.

Determining DR for Earthquake Event

Figure 5–3 is a reproduction of Figure 5–2 with the additional designation of a structural collapse zone along the south wall vulnerable to a seismic event. The affected equipment includes half of the dissolution glovebox and the final glovebox (No. 4) in the fuel fabrication line. A seismic study indicates all other gloveboxes and major equipment have sufficient margin to survive the seismic stress.

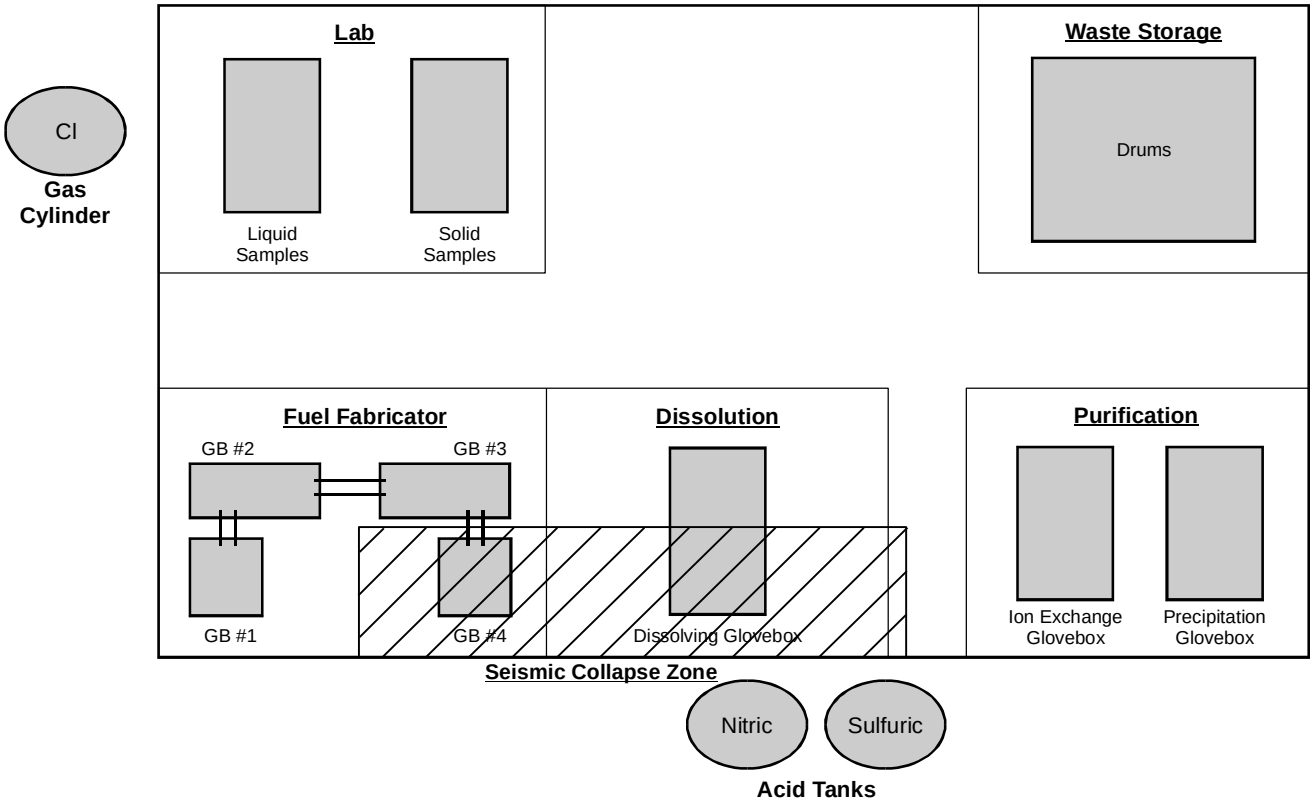

Figure 5-3. Seismic Collapse Zone.

Based on the batch operation discussions for this example in the MAR section, 3,000 g of material can be in the dissolution glovebox. Six thousand grams of powder from the precipitation operation can be in the fuel fabricator line, with 3,000 grams in the front end (i.e., glovebox #1), and 3,000 grams in the back end (gloveboxes #3 and #4).

At first glance, the largest source term of concern would occur if 3,000 g of powder is in glovebox #4, which is impacted by falling debris. A DR of 0.5 (3,000 of 6,000 g) would be assigned to this material, with an equal DR of 0.5 for the powder in undamaged gloveboxes # 1 and #2. The two separate 3,000 gram inventories are kept distinct as the multiple stresses experienced by material in the crushed glovebox will yield release in excess of the single effect of seismic shock in the intact gloveboxes. In this case, it is not correct to assume the powder in glovebox #1 is not MAR since it experiences a small release stress.

But suppose by the time the material reaches glovebox #4 that it has been rendered into a ceramic state impervious to the stresses offered by the structural collapse. The damage ratio for glovebox #4 might then be zero. At a minimum, the ARF for the stress imposed upon ceramic components would be significantly less than the ARF for the stress imposed upon powder. It is conceivable that the bounding release scenario might now move the 3,000 grams of material from glovebox #4 to glovebox #3, where it would still be powder and experience the limited release from seismic shock. These are the types of considerations that come into play when generating source term estimates.

Another possible source of airborne material would be the seismic vibration experienced by surface contamination in all four gloveboxes. This material might contribute in a minor way for the first three gloveboxes as it could have a larger ARF (for smaller quantities) than bulk powder contained in cans or equipment. It could even prove the dominant source term from glovebox #4 if the ceramic fuel forms in question truly are undamaged in the post-seismic state. This drives home again the point that the source term analysis assesses multiple factors. While individual factors should not be unrealistically exaggerated, no potential contributor should be dismissed without consideration.

Moving to the issue of the dissolution glovebox, consider two cases. In the first, the spray chamber and acid storage tank are located at the south end of the glovebox in the collapse zone. Both should be considered structurally compromised in the aftermath of such an event. The question is what value to assign for what MAR? In this case, the ARF for liquids will exceed that for metal. The accident analysis should therefore assume a full dissolution run of four items has finished and the liquid tank contains 3,000 grams of material in solution. The DR for this MAR is 1.0.

The second case is one where the spray chamber and acid storage tank are located at the north end of the glovebox, outside of the collapse zone. This would initially lead to an assumed DR of zero. If, however, the piping that transfers liquid out of the glovebox passes through the collapse zone, some release is possible. If the pipe is one inch in diameter, and the affected length is ten feet, with an additional twenty feet in the next room over that might drain back to this new low point, a total of 4.6 liters might be available to spill. This yields a DR of 0.15 (4.6 liters out of 30). Likewise, if the acid storage tank survived, but seismic analysis indicated failure of a penetration on the tank at the 15 liter level, 15 liters could be assumed to spill from the tank and 15 liters remain, yielding a DR of 0.5.

As a final note, analysts should realize that the structural strength of the majority of the facility, and the seismic capacity of the gloveboxes, is an initial condition of analysis. That is why the hypothetical analysis discussed above focused on areas of potential facility damage. For facilities and gloveboxes with significant inventory, that initial condition should be preserved as a TSR Design Feature.

5.2.3 AIRBORNE RELEASE FRACTION (ARF) AND RESPIRABLE FRACTION (RF)

5.2.3.1 OVERVIEW OF REQUIREMENTS, GUIDANCE, AND PRACTICES FOR DETERMINING ARF/RF[19]

DOE-STD-3009-2014 provides the following information/directions related to ARF and RF:

> *"The ARF is the coefficient used to estimate the amount of a radioactive material that can be suspended in air and made available for airborne transport under a specific set of induced physical stresses. The RF is the fraction of airborne radionuclide particles that can be transported through air and inhaled into the human respiratory system. The RF is commonly assumed to include particles of 10-µm Aerodynamic Equivalent Diameter and less. Bounding estimates, and in many cases median estimates, for radionuclide ARFs and RFs for a wide variety of MAR and release phenomena are presented in DOE-HDBK-3010. The bounding estimates shall be used unless a different value is provided in an applicable standard or is otherwise technically justified. In cases where direct shine may contribute significantly to dose, that contribution should be evaluated without the use of the RF, and without the use of the ARF if due*

[19] The convention "ARF/RF" is used throughout this Handbook, which is adopted from the DOE-HDBK-3010-94 that represents the pair of recommended bounding values that are multiplied together to determine the airborne source term, and does not represent dividing the ARF by the RF.

to a spill release resulting in exposure to a pool. ARFs and RFs are selected based on physical conditions and stresses anticipated during accidents. DOE-HDBK-3010 defines bounding ARFs and RF mechanisms and airborne release rates based on physical context."

DOE-HDBK-3010-94, defines ARF as "the coefficient used to estimate the amount of radioactive material that can be suspended in air and made available for airborne transport under a specific set of induced physical stresses. " RF is defined as "the fraction of airborne radionuclides as particles that can be transported through air and inhaled into the human respiratory system and is commonly assumed to include particles 10 microns Aerodynamic Equivalent Diameter (AED) and less." Particles greater than 10 microns AED are less likely to be transported into the lung, and thus are not as effective in imparting radiation dose to the body.

The ARF and RF are typically evaluated together except in circumstances where it is desired to know the total release of a given material, or when the RF is one, such as is the case with gases. Defining these two parameters generally presents the greatest difficulty in source term analysis. Historically, available information on the subject was extremely limited. As a result, whatever information could be found was used regardless of its true applicability. Little quality control was applied either: different ARFs were assigned by different analysts based on the same information, best guesses became quasi-facts with sufficient repetition, numbers were transposed in copying and passed down, etc. In response to this state of affairs, the DOE set in motion a project to collect the available data on ARFs for material at nonreactor nuclear facilities, test its application in real life circumstance, and attempt to define bounding values for various phenomena. This effort culminated in the development of DOE-HDBK-3010-94. The estimates from that document have since been reproduced in NUREG/CR-6410 and ANSI/ANS-5.10, *Airborne Release Fractions at NonReactor Nuclear Facilities*. Both of the documents cited were subject to significant peer review.

In the development of DOE-HDBK-3010-94, available experiments and other data were correlated with the major types of material forms present at materials handling facilities, as well as the normal accidents of concern for such facilities. The major types of material were considered to be: (1) gases, most specifically tritium; (2) liquid solutions, both organic and aqueous; (3) solids, including metals, bulk powders, aggregates, spent fuel and other special forms; and (4) surface contamination, whether in the form of holdup in processes, material entrained in waste, or soil contamination. The major types of accidents considered included spills, fires, explosions, seismically induced vibrations and impacts, and criticalities. The latter, while included in DOE-HDBK-3010-94, represent a special case whose potential MAR is directly defined by the physics of the phenomena itself.

The net result of correlating data to material and accidents was a general categorization of ARFs by four categories: explosive, thermal, mechanical, and aerodynamic entrainment (i.e., resuspension). Explosive stresses of interest are shock effects, blast effects, and venting effects associated with detonation (e.g., high explosive), deflagration (e.g., most gas explosions), and over-pressurization (e.g., heating confined material to rupture pressure). Thermal stresses include evaporation of liquids and combustion of organic liquids, combustion of solids and contaminated waste, and intense heating of noncombustible material. Mechanical stresses of concern include free-fall spill to impact, vibration/shock induced by events such as an earthquake, and impact or crushing of material and containers by falling debris. Aerodynamic entrainment relates to the special case of material freshly deposited on surfaces in the immediate aftermath of an accident or other release. Such material is especially vulnerable to wind forces resuspending it in the air in a way material that has settled for a lengthy period is not. In the latter case, the available data indicates the bounding values assigned for DOE-HDBK-3010-94 would be excessive, potentially by orders of magnitude.

Along with ARF values, associated RFs were assigned whenever possible. The size distribution of accident generated aerosols is a particularly complex issue, as most experiments cannot be designed so as to capture a truly representative sample. The logistical requirements of sampling typically result in a skewed sample. Either a sample is obtained where the larger size particles have already deposited due to sampling at a distance or engineered features of the sampling device itself, or the size distribution is affected by the physical chaos of the event itself (e.g., fire) on in-close sampling equipment. Further, this most basic of problems does not even address detailed physics interaction problems, such as the attractive forces between particles (inter-particle attractive forces) or between particles and the surface (including the effect of surface roughness and the presence of other materials that increase the adhesion of the particles to the surface).

Table 5-1, taken from Table A1 of ANSI/ANS-5.10, Bounding ARFs and Applicable Experimentally Measured RFs, presents a brief summary of ARF and RF values currently available. It is emphasized that this is only a summary, and the discussion of ARF selection to follow is both brief and general in nature. Analysts unfamiliar with the details of DOE-HDBK-3010-94 should not attempt to apply ARF and RF values using Table 5-1 or this chapter as a reference. ARF and RF values should be chosen using DOE-HDBK-3010-94, DOE-STD-5506-2007, NUREG/CR-6410, technical journal articles, from other approved DSA's, or derived from physics/chemistry principles. The source of the values needs to be cited and technically justified for use. As stated in the quote above, alternate values to the DOE-HDBK-3010-94 bounding values may be technically justified.

An ARF value is selected on the basis of the scenario postulated, the type and level of stress presumed to impact the MAR, and the characteristics of the MAR. Both volatile and nonvolatile materials can be suspended. To suspend a stable material at rest, it is necessary to impact the material sufficiently to convert it to a suspendible form and to provide sufficient air flow to carry the suspended material into the local flow field. In the case of volatile materials, the physicochemical environment to convert the material to its gaseous form needs to be present. If the conversion is due to a chemical reaction, sufficient reactant needs to be available to convert all the affected MAR to its gaseous phase. If the quantity of reactant necessary for conversion is limited and only converts a portion of the volatile material to its gaseous phase, the fraction converted becomes the ARF. In the case of material in the gaseous phase, no RF can be assigned, since, all the material can be transported and inhaled as long as the material remains in the gaseous phase. Airborne reactions, however, can either convert some gaseous materials to solid particles (e.g., reaction of NO_2^- with MH_4^+ to produce NH_4NO_3), attach them to existing airborne particles (e.g., attachment of I_2), or result in adhesion to surfaces (e.g., I_2).

Table 5-1. Summary of Bounding ARF and RF Values.

NOTES: This table is copied from ANSI/ANS-5.10-1998, *Airborne Release Fractions at Non-Reactor Nuclear Facilities* (Reaffirmed November 6, 2006).

The codes in the column titled "TSL" (Technical Support Level) indicate the following:

1 - supported by experimental data from more than one independent source of the stated range with experimental support for particle generation mechanism;

2 - experimental support over that stated range;

3 - single experimental datum or inferred from other studies.

In the "ARF (RF)" column, the value for the ARF is given in exponential form, and the value for the RF, where used , is given in decimal form, and in parentheses. Letters in square brackets ([a], [b], etc.) refer to notes at the end of the Table A1 as presented in ANSI/ANS-5.10-1998, Other minor formatting and editing changes were also made to the original Table A1, and any non-editorial changes to Table A1 are shown in *{italicized text}*.

Stress/Material	ARF (RF)	TSL	Reference*	Comments
Explosive Forces: Detonation				
Reactive Metal Implosion, Pu surrounded by and in intimate contact with high explosives (HE), HE:Pu ratio > 1 to 10, single point detonation	1E+0 (0.2)	2	Mensing et. al., 1995, Shreve and Thomas, 1965	Calculated from airborne sampling data for operation "Roller Coaster" 1965 (experiments to determine the dispersal of nuclear materials by explosives).
Implosion, metal surrounded by and in intimate contact with high explosives (HE); HE:metal ratio >1 to 10, single point detonation	2E-1	3	ANSI/ANS 5.10-1998	Based on small scale experiments on the dispersal of metal hemisphere by explosives. Applicable to metals less reactive than Pu. Release of any Pu is estimated by ARF/RF values shown.
Metal or Solution – Explosion, metal or aqueous solution, high explosive in intimate contact with material, HE:material ratio 0.07 to <1	TNT Eq. [a]	2	DOE Handbook, Sections 3.2.2.1 and 4.2.2.1	
Powder – Explosion, High Explosives lying on surface, HE:powder ratio 1 to 100	ARF x RF = 0.2 x TNT Eq. [b]	2	DOE Handbook, Section 4.4.2.1	From soil lofted during field tests where HE (bare and as artillery shells) were placed directly on the soil surface.
HEPA Filters *{Shock pulse}*	2E-6	2	DOE Handbook, Section 5.4.2.1	Small pieces of glass fiber medium were dislodged from a few locations on the creases in the downwind region of the filter.

Stress/Material	ARF (RF)	TSL	Reference*	Comments
Explosive Forces: Deflagration				
Powder Unshielded, directly under or in blast volume of large explosion with high confinement pressure	1E+0 [c]	2	DOE Handbook, Section 4.4.2.2.1	
In containers or at a distance of meters from the blast volume, aerodynamic entrainment by accelerated gas velocities	5E-3 (0.3)	2	DOE Handbook, Section 4.4.2.2.2	
HEPA Filters *{Venting by pressurized gases}*	1E-2	2	DOE Handbook, Section 5.4.2.2	
Explosive Forces: Over-pressurization to Rupture				
Liquid, confined in vessel or container Slow buildup of pressure [d], vented above the surface level of liquid, failure <0.35 MPa_g	5E-5 (0.8)	2	DOE Handbook, Section 3.2.2.3.2.A	
Slow buildup of pressure, vented above the surface level of liquid, failure pressure >0.35 up to 3.5 MPa_g	2E-3 (1.0)		DOE Handbook, Section 3.2.2.3.2.A	
Rapid buildup of pressure, vented above the surface level of liquid	NVA [e]		DOE Handbook, Section 3.2.2.3.2.B	
Rapid buildup of pressure, vented below the surface level of liquid [f]	1E-4	2	DOE Handbook, Section 3.2.2.3.1	
Superheated liquids ("flashing spray"), <50 ^oC superheat	1E-2 (0.6)	2	DOE Handbook, Section 3.2.2.3.3.A	
Superheated liquids ("flashing spray"), 50 ^oC – 100 ^oC superheat	1E-1 (0.7)	2	Mishima et. al., 1968, Borkowski et. al., 1986, and Kataoka and Ishii, 1983, DOE Handbook, Section 3.2.2.3.3.4	
Powder Confined in vessel or container, release pressure < 0.17 Mpa_g (< 25 psig)	5E-3 (0.4)	2	DOE Handbook, Section 4.4.3.3.2	
Confined in vessel or container, release pressure > 0.17 < 3.5 Mpa_g (25–500 psig)	1E-1 (0.7)	2	DOE Handbook, Section 4.4.2.3.1	
Vitrified High Level Waste Canisters High pressure sufficient to dissolve the plug	3E-5	3	DOE Handbook, Section 4.3.1.1	Based on a measured value of 3.5E-4 of inventory as particles in the upper plenum of canister and ARF/RF of 1E-1/0.7.
Thermal Stress				
Volatile compounds	1E+0	1	Brereton et. al., 1997	AP AC Spills Report.

Stress/Material	ARF (RF)	TSL	Reference*	Comments
Liquid, aqueous solutions				
Simmering, no visible bubbles	3E-5	2	DOE Handbook, Section 3.2.1.1	
Boiling [g]	2E-3	1	Mishima et. al., 1968, Borkowski et. al., 1986, and Kataoka and Ishii, 1983, DOE Handbook, Section 3.2.1.3	
Liquid, organic combustible	1E+0	2	DOE Handbook, Section 3.3.1, 3.3.7	
Volatile compounds				
Non-volatile compounds, burns to self-extinguishment, no significant surface turbulence	1E-2	2	DOE Handbook, Sections 3.3.1, 3.3.7	
Non-volatile compounds, vigorous burning with surface turbulence, burns to self-extinguishment	3E-2	2	DOE Handbook, Sections 3.3.3, 3.3.4, 3.3.5, 3.3.7	
Non-volatile compounds, vigorous burning with surface turbulence, to complete dryness	1E-1	2	DOE Handbook, Sections 3.3.3, 3.3.7	
Burning of combustible liquid over air-dried residue from solution on porous, non-heat-conducting surface	5E-3 (0.4)	2	DOE Handbook, Sections 3.3.6, 3.3.7	
Burning of combustible liquid over air-dried residue from solution on heat-conducting surface	2E-1 (0.3)	2	DOE Handbook, Sections 3.3.6, 3.3.7	
Solid reactive metal				
Plutonium, < ignition temperature [h] of oxide formed	3E-5 (0.04)	2	DOE Handbook, Section 4.2.1.1.2	
Plutonium, > ignition temperature	5E-4 (0.5)	1	Mishima, 1966, 1967; Luna, 1994; Carter and Stewart, 1970; Eidson et. al., 1988; Eidson and Kanapilly, 1983, DOE Handbook, Section 4.2.1.1.3	
Plutonium, free-fall spill of molten metal into air, small fall distance	1E-2	2	Stewart, 1963, DOE Handbook Section 4.2.1.1.4	
Plutonium, small drops of molten metal violently dispersed that travel greater than 1 m in air	1E+0 (0.5)	1	Raabe et. al., 1978, Chatfield, 1969, DOE Handbook Section 4.2.1.1.5	
Uranium, less than ignition temperature [i], greater than 500 °C	1E-3	2	DOE Handbook, Section 4.2.1.2.1	

Stress/Material	ARF (RF)	TSL	Reference*	Comments
Uranium, free-fall spill of molten metal greater than 1 m	1E-2	2	DOE Handbook, Section 4.2.1.2.2	
Uranium, explosive dispersal of thin sheets of metal	1E+0	2	DOE Handbook, Section 4.2.1.2.3	
Concrete				
Tritium (^3H) as water, > 20 °C to 200 °C	5E-1	2	DOE Handbook, Section 4.3.1.2	
Tritium (^3H) as water, > 200 °C to 600 °C	1E+0	2	DOE Handbook, Section 4.3.1.2	May also suspend radionuclides held in cement matrix if cement is decomposed and particles of CaO can be suspended.
Solid, powder				
Nonreactive [j], up to 1,000 °C, upflow around powder to 100 cm/s	6E-3 (0.01)	2	DOE Handbook, Section 4.4.1.1	
Reactive, plutonium compounds, up to 100 °C, upflow around powder to 100 cm/s: Plutonium fluoride	1E-3 (0.001)	2	DOE Handbook, Section 4.4.1.2	
Solid, Compounds				
Reactive, plutonium compounds, up to 100 °C, upflow around powder to 100 cm/s: Plutonium oxalate, nitrate	1E-2 (0.001)	2	DOE Handbook, Section 4.4.1.2	
Solid, contaminated combustible				
Packaged waste, burns to self-extinguishment	5E-4	2	DOE Handbook, Section 5.2.1.1	
Loose cellulosic material, burns to self-extinguishment	1E-2	2	DOE Handbook, Section 5.2.1.2	
Loose polystyrene	1E-2	2	DOE Handbook, Section 5.2.1.4.3	
Loose, other plastics	5E-2	2	DOE Handbook, Section 5.2.1.4	
Light cellulosic material remaining suspended during complete combustion (i.e., ash)				
UO_2 preformed particle	4E-1	2	DOE Handbook, Section 5.2.1.3	
Contaminated with air-dried residues from solution	8E-2	2	DOE Handbook, Section 5.2.1.3	
Solid, contaminated HEPA filters passage of heated air up to 400 °C [k]	1E-4		DOE Handbook, Section 5.4.1	

Stress/Material	ARF (RF)	TSL	Reference*	Comments
Aerodynamic Entrainment/Resuspension [l]				
Homogeneous Deposit				
Liquid, indoors, shallow pool on heterogeneous surface (e.g., stainless steel, glass, concrete), normal building ventilation flow/low airspeed (< 2 m/s, ~5 mph)	ARR: 4E-7/hr	3	DOE Handbook, Section 3.2.4.5	
Liquid, indoors, as above, covered with substantial layer of debris or indoor static conditions	ARR: 4E-8/hr	3	DOE Handbook, Section 3.2.4.5	
Liquid, outdoors, large pool, up to 13.6 m/s (~30 mph)	ARR: 4E-6/hr	3	DOE Handbook, Section 3.2.4.5	
Powder, pile on heterogeneous surface (e.g., concrete, stainless steel, glass), normal building ventilation flow/slow airspeed (< 2 m/s, ~5 mph)	ARR: 4E-5/hr	3	DOE Handbook, Section 4.4.4.1	
Powder, indoors, as above covered with substantial layer of debris or indoor static conditions	ARR: 4E-6/hr	3	DOE Handbook, Section 4.4.4.1	
Powder, dispersed into flowing air, airspeed up to 9.1 m/s (20 mph)	[m]	2	DOE Handbook, Section 4.4.3.2	
Heterogeneous Deposit				
Liquid, outdoors, absorbed on soil, no large standing pools of free liquid, up to 22.7 m/s (50 mph)	ARR: 9E-5/hr	2	DOE Handbook, Section 3.2.4.4	
Powder, indoors, loose surface contamination [n], normal building ventilation flow, low airspeed (<2 m/s, 5 mph)	ARR: 4E-5/hr	3	DOE Handbook, Section 5.3.4	
Powder, outdoors, due to the passage of vehicular traffic across or by loose powder on road, up to 22.7 m/s (50 mph)	ARR: 1E-2/ pass	2	DOE Handbook, Section 4.4.4.2	
Mechanical Stress [o]				
Free-Fall Spill				
Liquid, aqueous solution, spill distance < 3 m	2E-4 (0.5)	2	DOE Handbook, Section 3.2.3.1	
Liquid, slurry (<40 percent solids), spill distance < 3 m	5E-5 (0.8)	2	DOE Handbook, Section 3.2.3.2	
Liquid, viscous solution, spill distance < 3 m	7E-6 (0.8)	2	DOE Handbook, Section 3.2.3.3	
Liquid, spill distance > 3 m (see reference)			DOE Handbook, Section 3.2.3.1	

Stress/Material	ARF (RF)	TSL	Reference*	Comments
Powder, spill distance < 3 m	2E-3 (0.3)	1	Sutter et. al., 1981, Ballinger et. al., 1988, Plinke et. al., 1991, Heitbrink et al. 1992, DOE Handbook, Section 4.4.3.1.2	
Powder, spill distance > 3 m (see reference)		2	DOE Handbook, Section 4.4.3.1.3	
Powder, shock impact due to falling debris	1E-2 (0.2)		DOE Handbook, Section 4.4.3.3.2	
Powder, dispersed into flowing air, to 9.1 m/s (20 mph) (see reference)			DOE Handbook, Section 4.4.3.2	
HEPA filter, object strikes encased [p] filter or encased filter impacts unyielding surface after fall	5E-4	3	DOE Handbook, Section 5.4.4.1	
HEPA filter, object strikes unencased filter or unencased filter impacts unyielding surface after fall	1E-2	3	DOE Handbook, Section 5.4.4.2	
Spent nuclear fuel				
Noble gases	5E-2	2	Soffer, 1993	
Iodine (I_2)	2.3E-3	3	Mishima, 1995	
Cesium vapor	2.5E-4	3	Mishima, 1995	
Fines	2.4E-4 (7E-5)	2	Mishima, 1995	
Crush/Impact				
{Vitrified} Glass	[q]	2	DOE Handbook, Section 4.3.3	
Aggregate	[r]	2	Owczarski and Mishima, 1996	
Spent nuclear fuel				
noble gases	7E-2 [s]	2	Kent, et. al., 1995	For the degree of fragmentation in experimental program.
iodine (I_2)	2E-3	2		
^3H (as HTO)	1E-2	2		
Ffuel	2E-3 (7E-5)	2		Bounding for energy density (crushing force) imparted to material in the range of 10 to 100 J/cm^3.
Encapsulated ceramic oxide pellets, particles generated but not released, impact velocities of steel to 188 mph, concrete to 99 mph, and soil to 550 mph	5E-3 (0.6) *{[t]}*	2	Mishima, 1995	

Stress/Material	ARF (RF)	TSL	Reference*	Comments
Shock/Vibration				
Loose surface contamination *{powder}* *{contaminated noncombustible materials}*	1E-3 (0.1) *{(1.0)}*	2	DOE Handbook, Section 4.4.3.3.1 *{Sections 5.2.3.2, 5.3.3.2.2}*	
{Bulk powder]	*{1E-3 (0.1)}*	*{2}*	*{DOE Handbook, Section 4.4.3.3.1}*	
{Loose surface contamination, substrate packaged in container such as pail or drum}	*{1E-3 (0.1)}*	*{2}*	*{DOE Handbook, Section 5.2.3.2}*	

[a] A very conservative assumption of mass airborne in respirable size range (10 μm AED) is equal to the TNT Equivalent calculated for the explosion.

[b] Particles in the respirable size range of initial inventory made airborne, provided that this value does not exceed the fraction of *{respirable}*particles in the size range in the source material.

[c] RF for these events cannot exceed the fraction of *{respirable}* particles in the source material.

[d] Absorption and equilibration of gases in liquids is a function of chemical composition of the solution, the surface area and depth of the liquid, and the volume of the gas. Equilibrium may take minutes to hours dependent upon conditions.

[e] NVA = No value currently available.

[f] Generation of RF liquid droplets can be greater than the values shown here that bound circular, knife-edge orifices of 0.125-in diameter and greater with upstream pressures up to 200 psig. The "worst case" for RF droplets of solutions is a crack 50 micrometers wide. The longer the length, the more liquid that can be vented for a given upstream pressure. This type of crack is not a common nor typical occurrence for faults in pipes or vessels, and, at higher pressure, would probably propagate into a wider, longer crack. *{Note that this does not yet reflect the concern that 1E-4 ARF/RF is not appropriate for all spray releases, which led to the Hanford Waste Treatment Plant spray testing with PNNL – to be addressed after NSR&D technical report is completed.}*

[g] Only applies to bubbly flow (distinct bubbles visible, <30 percent liquid in form of bubbles). Does not apply to churn turbulent nor chaotic boiling regimes.

[h] Ignition temperature for plutonium metal is a function of surface to mass ratio (S:M). At S:M of 100 cm^2/g, the measured ignition temperature for plutonium metal is in the range of 160 ^oC. The ignition temperature rises rapidly after S:M 10 cm^2/g and ranges from 480 to 520 ^oC for bulk pieces.

[i] Like plutonium, the ignition temperature for uranium metal is a function of the Surface to Mass ratio (S:M). At S:M of 100 cm^2/g, the uranium ignition temperature is in the range of 200 ° C to 300 °C. Like plutonium it rises rapidly in the region of S:M 10 cm^2/g and reaches temperatures in excess of 700 °C or more. There is some doubt that bulk pieces of uranium can attain ignition conditions except for very special circumstances.

[j] Does not react chemically to change form under accident conditions postulated.

[k] Assumes HEPA filter medium (glass fiber) softens and melts at higher temperatures and thus retains particles accumulated on the fiber surfaces. *{This should not be taken as a presumption that filters will remain functional for prolonged exposure to temperatures up to 400 $^\circ$C.}*

[l] In this part of the table (the next nine items), the second column is the Airborne Release Rate (ARR), rather than ARF and RF.

[m] ARF = 0.0134[U] + 0.00543, where U is local windspeed in m/s.

[n] Loose surface contamination that can be removed by swiping or by low air speeds such as blowing across the deposit.

[o] From here to the end of the table, the second column is again ARF (RF).

Stress/Material	ARF (RF)	TSL	Reference*	Comments

[p] Encased denotes a container that does not £ail due to impact of falling objects nor impact with unyielding surface after fall of the container.

[q] Formula for crush/impact forces on brittle solids is shown on pg. 4-52 of DOE-HDBK-3010-94. For vitrified HLW, the empirical correlation 2E-11[J/cm^2] shown is applicable. The user should be cautious in application of this formula since the value calculated is an energy density applied to the material. If the crush/impact force is applied to all the material, the energy density is simply the force/volume. If the crush/impact force is only applied to a portion of the object (e.g., the object with mass and density only impacts a portion of the surface of the brittle material), the formula only applies to the volume being crushed.

[r] For aggregate materials such as cement, sandstone, etc., the correlation factor for use in the formula on pg. 4-52 of DOE-HDBK-3010-94 is 3E-11.

[s] For spent nuclear fuel, the empirical correlation is found in the NRC Safeguards Report (Kent, et. al., 1995).

{[t] Care should be taken in use of this value. It is based on extreme impact energies.}

* References from Section A3 of ANSI/ANS 5.10-1998 are as follows:

Ballinger, M. Y., J. W. Buck, P. C. Owczarski, and J. E. Ayer, *Methods for Describing Airborne Fractions of Free-Fall Spills of Powders and Liquids, NUREG/CR-4997* (PNL-6300), January 1988, Pacific Northwest Laboratory, Richland, WA.

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Stress/Material	ARF (RF)	TSL	Reference*	Comments

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In the case of liquids and solids, the material is either subdivided into droplets or particles, or, in the case of powders, is de-agglomerated. De-agglomeration of a powder at rest is not readily accomplished. This is especially true for stored powders, where the smaller particles have had time to settle into the interstices between larger particles. De-agglomeration/separation is difficult due to the small surface areas of small particles and the limited space for gas flow between them. Even in a heavier medium, such as a liquid, the application of sonic agitation for long periods (30 minutes or more) is necessary to restore a size distribution approximating the original distribution. All phenomena (including detonations with minimal stand-off distances) do not fragment small particles (<100 μm). Thus, the amount of particles in the respirable size range that can be suspended is limited by the amount of material of this size found in the original source powder.

Bulk solids and liquids require more energy to fracture the bonds that hold the form together. In the case of liquids, the material is drawn into a fine filament or sheet that breaks when the tensile strength of the material is exceeded. This can occur in many ways. If the liquid forms bubbles at the surface from boiling or the passage of a gas through the liquid, breakup of the bubbles generates fragments that can be suspended or result in secondary droplets when condensation of the liquid vapors. A mechanism that can form significant amounts of fine liquid droplets is a "flashing spray" that forms upon the venting to lower pressures of a liquid that is super-heated. The liquid initially forms a column approximately the shape of the opening. Then, bulk vaporization of the liquid (a significant fraction of the liquid is "flashed" into a vapor) within the column results in rapid subdivision of the remaining liquid. The greater the superheat, the smaller the diameter of the liquid droplets. In all cases of heated liquids, additional evaporation of the liquid occurs during airborne transport and, depending on the temperature, environmental factors, the distance traveled, and solute concentration, the droplet diameter decreases.

Bulk solids of various categories have different physical characteristics. For brittle materials (e.g., glass-like materials, aggregate, composites), crush-impact forces (including shock waves from explosions) can result in fragmentation. The level of force and the material tensile/compressive strength are factors that influence the particle size distribution of the fragments formed. Material that have elastic-plastic response to the application of forces (e.g., metal) require greater forces and are generally fragmented only by the pressures generated by the detonation of solid explosives in contact with the surface of the metal. Crush-impact forces generally result in deformation and tearing of metals; unless, the metal is embrittled.

One feature in particular of the data analysis is noted. ARF and RF values are assigned by physical context. That is, the physical context of the material determines the stress it experiences. For example, consider the case of powder spills. The bounding ARFxRF specified in DOE-HDBK-3010-94 for plutonium oxide powder falling freely through air is 6E-4. The bounding ARFxRF assigned if plutonium oxide falls inside a container is 1E-4. The difference is that the physics of release for the free-fall spill are driven by shear stress from air currents moving through the powder. That phenomenon physically does not exist inside a container. Release in the latter case is driven primarily by flexing of the container substrate upon impact with the ground, with some self-acting mitigation in the form of a powder's physical tendency to agglomerate. Therefore, if powder falls inside a can, acknowledging that point does not constitute improper crediting of a can in unmitigated analysis. For the perspective of DOE-HDBK-3010-94, the pedigree and capability of the can is irrelevant. The physical fact of it defines the stress being experienced by material. Further, it is not reasonable to assume personnel carry plutonium powder about cupped in their hands. In unmitigated analysis, however, if the can is not to be credited, it should assume to open upon impact with the ground and release the appropriate source term (i.e., can inventory * 1E-4).

The treatment of TRU waste is another such example. The respirable release fraction for loosely strewn waste in a fire is 1E-2. But packaged waste, even in as primitive a form as plastic bags or pails, is assigned a respirable release fraction of 5E-4. The experimental data supports that distinction due to the physical fact that a clumped mass traps particles in a self-filtering effect.

5.2.3.2 EXAMPLES FOR DETERMINING ARF/RF

Given that it is not desired to use this document as a primary reference for selecting release fractions, the reader is referred to the extensive examples in Chapter 7 of DOE-HDBK-3010-94. Only a brief discussion regarding one aspect of the example previously cited in Section 4.2.1, Material at Risk, is provided. It is intended to demonstrate the basic thought process for ARF selection.

A. Case One

Consider the example facility of Figures 5–2 and 5–3, specifically the fuel fabrication line. Presume for the moment that the structural collapse depicted in Figure 5–3 does not occur and all four gloveboxes remain intact (i.e., upright in a largely undamaged state) during a seismic event. What stress is then being imposed on any powder contained in the glovebox?

The four main categories of potential stress are explosive, thermal, mechanical, and aerodynamic entrainment. No explosion or fire is postulated for this event. No debris impacts either the powder or its outer glovebox confinement. This could lead an analyst to dismiss mechanical impact as well, but that would be a mistake, because even intact gloveboxes will experience transitory movement of structural members and an associated seismic vibration. If the gloveboxes held only solid metal, such a stress would present no significant force. For the much more fragmented powders, however, that force is sufficient to produce a small amount of aerosolization.

Examining Table 5-1 for mechanical stresses indicates that an ARF and RF of 1E-3 and 0.1, respectively, are assigned for shock/vibration of bulk powders. Previous examinations of this case have indicated the maximum MAR is 6,000 g of plutonium oxide powder for all four gloveboxes. The initial source term would therefore be 6 g, and the initial respirable source term 0.6 g.

Given this 0.6 gram respirable release, could surface contamination produce a significant contribution? Table 5-1 indicates that the ARF and RF for shock/vibration of loose surface contamination is assigned an ARF and RF of 1E-3 and 1.0, respectively, thus yielding a combined ARFxRF one order of magnitude greater than that for bulk powder. If significant contribution is defined as 10 percent of the 0.6 gram source term, then surface contamination would have to contribute 0.06 g of airborne material to be significant. Working backward with the ARFxRF of 1E-3 yields a required surface contamination MAR of 60 g. That is certainly possible given that historical surface contamination levels for representative gloveboxes can range up to 50 g. Using a value of 0.1 g/ft^2 for powder handling gloveboxes (from historical experience), and assuming each glovebox is 12 feet by 4 feet by 4 feet (with a factor of 1.3 applied for equipment inside the gloveboxes) yields a total MAR of 116 g for all four gloveboxes. It can be concluded, therefore, that surface contamination is a nontrivial contributor.

This last result points out another question that an analyst should always keep in mind: when is a result real, and when is it an artifice of analysis? Examining the specifics of DOE-HDBK-3010-94 indicates that the main reason the ARFxRF for surface contamination is assigned a higher value than for bulk powder is because no real confidence existed as to a generic size distribution for surface contamination residues. It is, in essence, simply a conservative assumption. DOE-HDBK-3010-94 contains multiple

cautions against taking its bounding recommendations as absolute statements of reality, or as a starting point for extrapolating ever more extreme circumstances that could theoretically exacerbate the physics of release. Either of these approaches can quickly tumble over into analytical gamesmanship, defeating the cited purpose of DOE-HDBK-3010-94, which is "to provide information to support general bases for decision making."

B. Case Two

Consider again the example facility of Figures 5-1 and 5-2, specifically the fuel fabrication line. Presume for the moment that the structural collapse depicted in Figure 5-3 does occur, but is sufficiently severe to collapse all four gloveboxes. What additional stresses are then being imposed on any powder contained in the glovebox?

Depending on how the powder is contained, and the nature and orientation of the debris impacting gloveboxes, it may not experience much in the way of additional stress. In the interests of conservatism, however, that is not typically presumed for the type of gloveboxes common in the DOE weapons complex. The collapse is instead broken down into the sequence of distinct events occurring. First, the glovebox is experiencing a fall of some kind, more so if it tips over than if it simply slumps downward, but the latter is considered equal to the former given that it is difficult to specify the exact nature of the collapse. Second, the glovebox is impacted by debris. Windows can break or contents can be spilled out of the glovebox. Either case raises the possibility of debris impacting powder.

For spill distances less than three meters, Table 5-1 specifies an ARF and RF of 2E-3 and 0.3, respectively, for the free-fall spill of powders. This circumstance is not, in fact, a free-fall spill, but the experimental data on free-fall spills is the closest equivalent available. Any conservatism involved in the use of this ARFxRF is simply accepted. Table 5-1 also lists an ARF and RF of 1E-2 and 0.2, respectively, for debris impacting powder. This might not be considered if the nature of the debris is small fragments or if the gloveboxes are shielded by slumping installations in the overhead. That will not be presumed to be the case. If the box contains loose powder that falls and is heavily impacted by debris, the cumulative ARFxRF could be as high as 6E-4 + 2E-3 = 2.6E-3.

Conversely, suppose all powder in the glovebox is held in cans or other metallic containers. The overall effect might then be characterized as two similar events. The can falls with the glovebox and is impacted by debris as it lands. As noted, DOE-HDBK-3010-94, the ARFxRF for shock impact and falling debris on confined bulk powder is 1E-4. The cumulative ARFxRF could therefore be as low as 1E-4 + 1E-4 = 2E-4. In this case, however, the idea of powder being outside of a container while in a glovebox is not an absurd construct similar to personnel carrying plutonium cupped in their hands outside of a glovebox. If the operation naturally lends itself to the powder being confined, that initial condition should be preserved in the TSR control set.

5.2.4 AIRBORNE RELEASE RATE (ARR)

Sometimes ARFs are expressed as a function of time. The parameter is then identified as an airborne release rate (ARR). This is, in fact, the norm for chemical releases. Gas escaping from a damaged cylinder will leak at a rate of so many pounds per second. Liquids spilled into a bermed area or as a shallow pool dispersing to its limits will evaporate at a rate of pounds per minute, depending on the surface area of the pool, its temperature, and the specific physical properties of the liquid.

Radionuclides are typically treated in a more overall fashion, as noted in the examples of Section 5.2.3, Airborne Release Fractions and Respirable Fractions. Most radioactive material releases occur due to momentary chaotic stresses. Therefore, even when the release might occur over a minute or several minutes, the total quantity airborne is assumed to exit the facility at one moment in time. That is often the case even for an event such as a fire, which occurs over an interval of tens of minutes, sometimes even hours. In these cases, unlike with the leak rate of a gas of a given pressure or the evaporation of a pool of a given liquid, there is no simple physical principle from which to compute reasonable time dependence. Even when the release is assumed to occur over some interval for atmospheric calculations, the total source term is simply divided by a general estimate of that time (e.g., 30 minutes, 1 hour). The most common exceptions to this are solution criticalities (whose time for a complete set of pulses is part of the event definition) and aerodynamic entrainment, which is defined as a rate. Chemical releases are discussed further in Section 5.3.

<u>Example</u>

It is not unreasonable to assume that an event as severe as the earthquake assessed in the Case Two example from the previous section could result in cleanup activities being delayed for some period of time. Aerodynamic entrainment will suspend more material during that period. How should that release be estimated?

A typical assumption is that for long duration releases, DOE-STD-3009 limits the unmitigated consequence analysis to eight hours. Table 5-1 defines an ARR of 4E-6 per hour for “powder, indoors ... covered with substantial, layer of debris or indoor static conditions.” Using that value, the ARR for 6,000 g of spilled oxide powder would be 2.4E-2 g/hr, or a total of 0.2 g/8 hr. If this figure were trivial compared to the overall facility release, it could either be ignored or lumped in with the immediate release.

5.2.5 LEAKPATH FACTOR (LPF)

The term “leakpath” refers to the path taken by material released in a facility on its way to the outdoor atmosphere. Common leak paths of a building are air ventilation ducts, door gaps, and various building leaks. The “leakpath factor” is the fraction of the radionuclides in the aerosol transported through some confinement deposition of filtration mechanism (DOE-HDBK-3010-94). The LPF used in the common five-factor formula is the total fraction of respirable airborne material released during the accident that escapes from the building to the environment. Once an aerosol is formed, it continuously depletes (in concentration) due to natural mechanisms such as gravitational settling and other lesser important mechanisms such as impaction, agglomeration (a subset of gravitational settling), diffusion to surfaces, and possibly mechanical filtration. The LPF is of interest because it has the potential for reducing the initial source term (IST) at the point of generation before it exits the facility, thus producing a much smaller release to the external environment.

The DSA analysis does not allow credit for a facility LPF for unmitigated analysis. Unmitigated analyses necessarily start with LPF of 1.0. For mitigated analysis, the LPF is dependent on the physical characteristics and configuration of the facility as it is estimated to exist under the postulated accident conditions.

Assignment of an LPF of 1.0 is the general practice for most low consequence facility DSAs. As accident consequences from bounding events increase into the rem range for the offsite public, LPF determinations become important and a process/strategy for estimation of a LPF < 1.0 generally becomes appropriate, such as crediting filtration or other natural depletion mechanisms.

Other than for filtration systems, LPFs are functions of building ventilation, building leak-tightness, atmospheric conditions (i.e., wind speed), building pressurization by a fire, the length of the leakpath, floor area for deposition of particulates, and other factors. Therefore, they are specific to the building and the location of the source within that building, and are specifically estimated for each scenario and building. Therefore, the effort in estimating the LPF is significant and the analyst should consider that there may be limited benefit for refinement of LPF below 1.0 for facilities with a small MAR.

Historically, some DSAs have been developed applying complicated in-facility transport analyses using the MELCOR or CONTAIN codes. Egress doors being open during evacuation have been considered for both normal ventilation and loss of ventilation scenarios. Also, based on these types of computer code analyses, and/or hand calculations, DSAs have credited an in-facility transport leakpath for station blackout evaluations, or loss of power concurrent with radiological material release within the facility. Under such scenarios, doors open during evacuation and otherwise closed doors with some assumed leakage past the door seals have been considered. The adequacy of those LPF justifications has been determined based on facility-specific ventilation designs, specific circumstances and postulated accident environments; approved by local Safety Basis Approval Authorities. The need for TSR controls would also be decided for a facility-specific situation.

Many LPF estimates are assumption-driven, can be challenging to defend, and should be carefully applied. Therefore, it is always important to remain cognizant of the inherent uncertainty in the LPF due to analytical variances in all of the parameters used in the assignment. As is the case with all safety analysis calculations, sufficient conservatism is factored into the overall determination by reasonably conservative assignment of the respective input parameters.

5.2.5.1 FILTRATION LPF

If a release passes through filtration before reaching the atmosphere, the LPF would be a function of High Efficiency Particulate Air (HEPA) filter(s) as it performs under the postulated accident conditions. A conservative LPF assumption based on filter efficiency (i.e., LPF = 1 – efficiency) for the accident conditions being evaluated should be made.

General guidance on HEPA filter design, installation, testing, and service life is provided in Chapters 3 and 8 of the DOE Handbook DOE-HDBK-1169-2003. HEPA filters, by definition, have a minimum filtration efficiency of 99.97% for 0.3 µm particles (the most penetrating size). For accident analysis, DOE-HDBK-1169-2003 states the following:

> *"Accident analysis typically assumes a first stage credit of 99.9 percent efficiency (DF of 10^3) for removal of plutonium aerosols. Second and subsequent stages typically assume an efficiency of 99.8 (DF of 5×10^2)."*

This assumption is predicated upon the filters in question having been leak tested upon installation and tested thereafter in accordance with national standards. The efficiencies assigned translate to LPF values of 1×10^{-3} for 99.9 percent and 2×10^{-3} for 99.8 percent. Thus, one stage of HEPA filtration has an LPF of 1×10^{-3}; two stages of HEPA filtration have an LPF of 2×10^{-6}.

Section F.2.1.3 of NUREG/CR-6410, provides the following additional guidance regarding HEPA filter efficiencies to mitigate accidents:

> *"… HEPA filters must demonstrate a particle collection efficiency of >99.97 percent for 0.3-µm diameter particles and have a particle collection efficiency of >99.95 percent for similar sized particles in-situ (installed in the system). For accidents in which conditions at the HEPA filter are unchanged from normal operating conditions, use of the in-situ tested efficiency is recommended for analysis (Elder, et al. 1986). If a series of HEPA filters is protected by pre-filters, sprinklers, and demisters, efficiencies of 99.9 percent for the first filter and 99.8 percent for all subsequent filters is recommended for accident analysis (Elder, et al. 1986). If conditions are severe or the filters are unprotected, efficiencies as low as 99 to 95 percent are recommended (USNRC 1978)."*

Even if tested after installation and periodically to meet industry standards, some DSA mitigated analyses have credited a smaller LPF (e.g., 0.01 or 0.1) since that was sufficient to reduce the unmitigated offsite and CW doses to low consequences, such as those defined by Table 2-8, Consequence Thresholds. However, if unprotected, the filter may be breached by flame impingement which will open up the leak path to near unity or it may be located remote from flame but be plugged by soot. No guidance is provided for these cases as the LPF is scenario and facility-dependent.

5.2.5.2 LPF MODELING

A more realistic estimation of the LPFs associated with complex pathways (e.g., rooms, corridors, stagnant supply and exhaust ducting) other than HEPA filtration also have the potential to significantly reduce release estimates for the DSA mitigated analysis (Ma, 2006). If the release passes through long passageways, cracks, or torturous routes before exiting to the atmosphere, fall-out and plate-out can be considered in determining LPF. It is possible to calculate how much material of a given size range will deposit out in the time it takes to navigate the available release paths. When multiple paths are present, LPFs may be specified individually for each path, or may be summed into one overall LPF. In more complex cases, each path will typically be assigned its own LPF. As the LPF for aerosol particles depends on particle size, multiple LPFs may be assigned for various size ranges as well.

Determination of LPFs less than unity takes a variety of forms. Quantitative LPFs can be performed by hand or by using a variety of computer codes, each dependent upon the complexity of the facility, the specific release parameters and the magnitude of unmitigated accident consequences. As would be

expected, small LPFs require substantial justification, particularly if the LPF is the dominant parameter and necessary in the reduction of accident consequences below the safety classification guidelines discussed in Chapter 8.

Because of this strong dependency on the facility and phenomenology of the release, default LPF values are not recommended. There are several hand-calculation methods to calculate the parameters that go into developing a LPF. One method is NUREG/CR-6189, *A Simplified Model of Aerosol Removal by Natural Processes in Reactor Containments* (SNL, 1996), which is available at http://www.osti.gov/bridge/servlets/purl/270806-1AhxgZ/webviewable/270806.pdf .

Another hand calculation method is LA-UR-03-7945, *Attenuation of Airborne Source Terms in Leak Paths* (LANL, 2003). A third method is presented in UCRL-CONF-220799, *The Resistance of HEPA Filters in a Ventilation Duct on Leakpath Factor Calculations* (Ma, 2006).

Chapter 4, Transport Within Containment/Confinement, of NUREG/CR-6410, also provides guidance on calculating LPFs. It describes the phenomena that control transport through buildings (i.e., ventilation and other flows of air, filters that remove particulates, and various effects such as gravitational settling, impaction on surfaces, thermophoresis, etc.). A portion of the introduction to that chapter is reproduced as follows:

> *"This chapter describes in-facility transport and deposition of gases, heavy gases, vapors, and particles, together with controlling parameters, basic aerosol physics, and airborne chemical reactions. The chapter emphasizes airborne particles, because such aerosols seem to predominate in accidents that might occur in fuel cycle facilities. The quantitative value that expresses the fraction of initially airborne material that successfully escapes the facility is called the Leak Path factor (LPF). For particles, the LPF primarily depends on three parameters: the flow rate of the aerosol through the facility, the particle sizes, and the areas available for deposition of contaminants.*
>
> *The objective of this chapter is to provide the tools necessary for defining the fraction of accident generated airborne material that escapes the facility and, if desired, the concentrations of airborne material throughout the facility as well as the amount of initially airborne material that has deposited within the facility.*
>
> *This chapter continues the accident analysis process whereby the source term provided in Chapter 3 is carried through and out of the facility. The primary final output is the fraction (for particles, the RF) of the source term that escapes the facility, the LPF. Secondary outputs are the concentrations and amounts deposited in the facility of the initial source term. To obtain these outputs, Chapter 4 provides guidance to help the user: (1) identify the facility barriers that define the flow path of the airborne material in the facility; (2) quantify the driving forces moving material along the flow path; (3) quantify the flow rates along the path; (4) quantify the effects of any mitigating engineered safeguards (e.g., filters); (5) quantify the roles of deposition processes along the flow path; and (6) estimate facility concentrations during the movement of the airborne source term."*

Computer codes can be used to support LPF calculation for the mitigated analysis. Computer code calculations should be considered for highly complex facility configurations where multiple release paths exist and the relative importance of the various leak paths is not obvious. The computer codes are also extremely beneficial in the cases of time-dependent phenomena (e.g., propagating fires) and when the

contaminant transport processes are complex, such as is the case where wide particle size distributions and coupled transport and deposition (e.g., agglomeration) processes exist.

The DOE Central Registry Toolbox code, MELCOR (Methods for Estimation of Leakages and Consequences of Releases), has been applied for some DOE nonreactor nuclear facilities and DOE has established code guidance supporting its use. MELCOR is a fully-integrated, engineering-level computer code whose primary purpose is to model the progression of accidents in light water reactor nuclear power plants. Major uses of MELCOR for non-reactor facilities include estimation of confinement behavior due to radiological source terms under postulated accident conditions, and their sensitivities and uncertainties in a variety of applications, evaluation of LPFs, and survivability of fans, filters, and other engineering safety features. A conservative LPF analysis should be consistent with the guidance provided in MELCOR Computer Code Application Guidance for Leak Path Factor in DSA Final Report that has been issued identifying applicable regimes in accident analysis, default inputs, and special conditions for using the code.

5.3 CHEMICAL RELEASE SOURCE TERMS

The MAR is the bounding quantity of a toxic chemical or mixture of toxic chemicals that is available to be acted upon by a single or series of physical stresses or insults from a postulated accident. Toxic chemical source terms may be evaluated using DOE-HDBK-3010-94, if appropriate for a non-reactive toxic chemical release phenomenon, however, the burden of proof is on the analyst to establish whether the bounding value or formula presented in that reference is representative of the accident phenomenology. This includes airborne particulates suspended from accident stresses on solids, as well as the particulates from the non-flashed portion of pressurized liquids, and all non-pressurized liquids that evaporate into gaseous source terms, or are entrained aerodynamically over time; all using the five-factor formula.

Another option to the five-factor formula available to the analyst to calculate toxic chemical liquid and gas release source terms is Environmental Protection Agency (EPA) 40 CFR Part 68 methodology for worst-case scenario development provided in "*Risk Management Program Guidance for Offsite Consequence Analysis*" (EPA 550-B-99-009, March 2009, or successor document). Detailed guidance, in Chapter 3 of that reference, is generally appropriate for determining release rates and quantities for a full spectrum of releases of toxic chemical gases and liquids. However, that EPA reference does not provide guidance for airborne particulates suspended from accident stresses on solids.

ARFs and RFs, which are highly dependent on particle size distributions and evaporative effects on aerosols, are selected based on physical conditions and stresses anticipated during accidents. For calculating toxic chemical releases from gases and liquid evaporation, the EPA methodology, which is more current, is preferred. If the EPA methodology does not provide relevant guidance for the accident scenario being modeled, DOE-HDBK-3010-94 defines bounding ARF and RF mechanisms based on the physical context of the accident stress. These include phenomena such as BLEVE from a fire around a tank, and shock or blast effects (e.g., overpressures) from an explosion or detonation. These are described in more detail in Section 4.3, Explosion Analysis, and in Section 7.5, Toxic Chemical Release Phenomenology and Subsequent Atmospheric Transport and Diffusion.

Section 5.2.4, Airborne Release Rates (ARR) and Table 5-1, Summary of Bounding ARF and RF Values, summarize airborne release rate recommendations from DOE-HDBK-3010-94 that are applicable to aerodynamic entrainment of radioactive materials as a function of time. Those recommendations may also be applicable to toxic chemical releases (i.e., wind resuspension of toxic chemical powders or evaporated precipitates from liquids).

The toxic chemical source term calculation results in a constant release rate in units of mass/time, or total release quantity in units of mass coupled with a specified release duration in units of time. For pressurized gas and pressurized liquid releases, the release rate varies over time, as indicated in Section 7.5. If the toxic chemical source term is not calculated as a constant airborne release rate over the accident duration for solids or pool evaporation rate for liquids and gases, the total airborne release quantity should be divided by the release duration consistent with the postulated scenario assumptions, or by recommended conservative estimates from the aforementioned guidance documents.

The source term is then subjected to a dispersion analysis to estimate toxic chemical concentrations to the CW and to the public (i.e., MOI). If the source term is calculated as a release rate, the accident duration is not used to calculate a peak airborne concentration. Instead, toxicological consequences of a release are based on the peak air concentration at the receptor location that occurs any time during the duration of the release, as discussed in Section 7.4, Chemical Health Effects on the Human Body. The toxic chemical concentrations at the CW, MOI and any other key receptors are then compared to the applicable chemical health effect indicators, called PACs/TEELs, depending on the toxic chemical, to determine the need for SS controls, as also discussed in Section 7.4. The PAC/TEELs are described in detail in DOE-HDBL-1046-2008.

A number of variables can influence the generation of the source term. These include the duration of the release and its subsequent effects on toxic chemical dispersion in the atmosphere. These cases should be evaluated with an appropriate DOE "Toolbox code" that is capable of evaluating more complex release mechanisms. These include: (1) pressurized liquid release two-phase flow; (2) pressurized gas release choked flow; and, (3) pressured gas release unchoked flow with variable release rate. Section 7.5 provides additional discussion on these topics. If a toolbox code is not available to address a particular phenomenology, a modeling protocol, as described in Section 6.1.11, should be prepared and appropriate approvals obtained. Chapter 7 provides additional discussion on attributes of toxic chemical codes and their limitations.

Section 7.8, Toxic Chemical Consequence Scoping Methodology to Exceed PAC Values, provides a simplified quantitative scoping methodology for determination of toxic chemical quantities that are sufficient to challenge the SS criteria. For this scoping calculation, conservative facility-wide estimates of ARF were based on values used for hazard categorizations. However, other conservative estimates of release fractions or release rates that would be appropriate to conservatively estimate chemical consequences for the hazard evaluation can be alternately justified in the modeling protocol.

5.4 APPROPRIATENESS OF SOURCE TERMS

The brief discussions and associated examples in Section 5.2 should serve to clarify that source term determination is not an exacting science. Instead, it involves a reasonable definition of circumstance, which is then broken down into a sequence of oversimplified parameters. This limited representation of reality demands a certain degree of conservatism to overcome the uncertainties introduced by the simplification.

No source term can account for all of the parameters introduced by first engineering principles, and this process may be subject to abuse. As an example, consider a glovebox with plutonium-239 powder collapsed by a seismic event and associated falling debris. It is possible to define the event so as to eliminate any consideration of the ARF×RF of 2 E-3 associated with debris impacting the powder even if the actual facility configuration does not support such an assumption. This can be done by making poor assumptions relative to shielding effects or the nature of the debris falling, or by probability arguments that are not defendable. This can be minimized by standardization, expert elicitation and independent

review. DOE-HDBK-3010-94 was prepared to facilitate the development of some consensus among DOE oversight and facility operators regarding a conservative estimate of consequence potentials. That consensus is necessary to effectively implement integrated safety management by minimizing the subjectivity in source term assessment.

The basis for determining source term appropriateness is to use a combination of parameters on the upper end of any potential uncertainty. That does not mean an average value, or even a 95th percentile value, since meaningful informed statistical distributions cannot be generated for most of the accidents under consideration. Instead, it means that a general consensus exists on upper and lower bounds for the cumulative scenario definition and associated parameter specifications, which should yield a source term in excess of the actual event that is not excessively conservative.

5.4.1 ADEQUATE TECHNICAL BASIS TO DEPART FROM DEFAULT OR BOUNDING VALUES

Section 3.2.4, Consequence Calculations, of DOE-STD-3009-2014 states:

> *"Calculations shall be made based on technically-justified input parameters and underlying assumptions such that the overall consequence calculation is conservative. Conservatism is assured by the selection of bounding accident scenarios, the use of a conservative analysis methodology, and the selection of source term and input parameters that are consistent with that methodology.*
>
> *For some input parameters, this section identifies default or bounding values that may be used without further justification. Unless otherwise stated for a particular input value, this section allows use of alternative values when supported by an adequate technical basis. When an input parameter used is not a default or bounding value, an acceptable technical basis of the value describes why the value selected is appropriate for the physical situation being analyzed, and references relevant data, analysis, or technical standards. The completeness and level of detail in the technical basis should increase as the parameters depart from default or bounding values. DOE is developing an Accident Analysis Handbook which will provide additional discussion on conservative consequence calculations."*

Additional guidance to develop an adequate technical basis that departs from default or bounding values is the focus of this sub-section. There are two fundamental reasons for departing from default or bounding values:

1. It may be expedient to use clearly bounding and conservative values to demonstrate that no controls are necessary, which will result in a simplified analysis; and,

2. Default values for a specific site may be too conservative leading to unnecessary burdensome controls.

For expediency, the analyst may perform a consequence calculation by simply using clearly bounding assumptions along with bounding and/or default input parameters provided in DOE-STD-3009-2014, DOE-HDBK-3010-94, or other sources (e.g., NUREG/CR-6410), because the values to be used are easily identified and readily defended as bounding and conservative. The dispersion analysis Option 2 discussed in Section 6.1.10, DOE-STD-3009-2014 Atmospheric Dispersion Options, is an example using this approach. If such a consequence calculation shows that no controls need to be SC or SS, then no

refined or more complicated calculation is needed to classify controls. However, this approach generally results in an overestimate of consequences and likelihoods, sometimes by orders of magnitude. If this very conservative calculation yields consequences that exceed thresholds for control classification, a more refined analysis is typically performed unless implementing and protecting the controls derived from the simplistic analysis has a small impact on schedule and cost, especially lifecycle cost. As calculations are refined, conservatism in the analysis is reduced, with appropriate technical justification, but no further than the point where either: (1) individual input parameters and underlying assumptions are less conservative than a best estimate (i.e., mean value) of their expected values during the accident scenario; or, (2) the overall result of the consequence calculation is not conservative. Option 3 in Section 6.1.10 is an example using this approach to refine calculations after the required approvals are obtained.

Three requirements in DOE-STD-3009-2014 are important to providing assurance that consequence calculations are conservative for plausible accident scenarios, NPH events, and external man made events:

(1) "MAR values used in hazard and accident analysis shall be consistent with the values noted in hazard identification/evaluation, and shall be bounding with respect to each accident being evaluated.[7]" [Section 3.2.4.1]

[7] For facilities that provide retrieval, handling, storage or processing of TRU waste containers, a bounding MAR may be determined in accordance with DOE-STD-5506-2007.

(2) "Radiological consequences are presented as a TED based on integrated committed dose to all target organs, accounting for direct exposures as well as a 50-yr commitment." [Section 3.2.4.2]

(3) "While the three options allow for alternative methods to calculate the χ/Q values, all three options shall evaluate the dose at the MOI using either a 95th percentile for a directionally independent method or a 99.5th percentile for a directionally dependent." [Section 3.2.4.2]

When default values are too bounding and too conservative, resulting in unnecessary controls for unrealistic scenarios, input parameters can be adjusted if there is sufficient technical justification to show that the input parameters used are still bounding. The rationale could be based on new representative experimental data on release fractions, or based on evaluation of the experimental data used to recommend bounding ARFs/RFs in DOE-HDBK-3010-94. For example, a bounding value for a free-fall spill of powders is based on a drop at a 3-m height. Typical glovebox operations in nonreactor nuclear facilities requiring manual operations could be evaluated based on a 1-m fall height for either a spill within the glovebox, or a seismic-induced toppling of the glovebox[20] based on the experimental data that provided the basis for the 3-m spill. Considerations should include, but not be limited to, the following factors:

(1) Representativeness of the data to the accident scenario being evaluated;

(2) Completeness of the data (e.g., is it based only on a few samples);

(3) Pedigree of the data; and,

[20] Other release mechanisms are also applicable as discussed in the DOE-HDBK-3010-94, Chapter 7.0, Application Examples, (e.g., shock and vibration as the glovebox impacts the floor, or air turbulence if the structure collapses onto the glovebox).

(4) Available data on particle sizes within the application domain of the calculation.

As a matter of practice, detailed statistical analyses are not necessary, nor expected. A review of the experimental data and what percentile ranking the selected alternate value is may provide some insights for the decision. However, the DOE-HDBK-3010-94, Section 1.3, Applicability of Data, provides cautions regarding interpretations of the experimental data and that the experimental data should not be used as a basis for an ARF statistical distribution.

In some instances, the data available to support selection of input parameters are not prototypic of the situation being analyzed, or there is large uncertainty. Hence, sound technical judgment is essential in selecting appropriate input values, considering the range of possible values given the physical and chemical conditions involved with the accident scenario and the relevant uncertainty. Although some degree of subjective engineering judgment may be necessary, the rationale needs to have a technical basis and not just opinions. Expert elicitation is essential to the success of this process.

The completeness and level of detail of the rationale used in technically justifying individual input parameters increases as the parameters approach more realistic values. The methodology used in selection of input parameters and analysis should not lead to unrealistic accident scenarios and consequence estimates, nor an overall realistic estimate of consequences that may be appropriate for a comprehensive probabilistic risk assessment (PRA) study. The burden is on the safety analyst to justify that the overall consequence estimates will be sufficiently conservative for the purpose of determining the need for safety SSC or SACs.

6 ATMOSPHERIC DISPERSION AND RADIOLOGICAL CONSEQUENCE ANALYSIS

Radiological and/or chemically hazardous materials released into the environment can be transported to potential receptors through air and water pathways. This chapter discusses the mechanisms of atmospheric transport and diffusion, collectively referred to as *dispersion*, of such pollutants. The dispersion of radioactive materials is discussed in this chapter and that of chemical materials in the next. Chapter 7, *Chemical Dispersion and Consequence Analysis*, only discusses dispersion principles specific to chemical releases (such as dense gas dispersion), as much of the discussion of the transport of radioactive materials can be applied to the transport of chemical materials as well.

This chapter and its associated appendices (E and G) address both the dispersion of radioactive materials and their consequences, once the source term (ST, in Ci) is estimated, as discussed in Chapter 5. This meets the requirements of Section 3.2.4.2 of DOE-STD-3009-2014 (DOE, 2014), *Radiological Dose Consequence*.

The basic equation for the calculation of radiological inhalation dose to a downwind receptor is:

$$Dose\ (rem) = ST \times \chi/Q \times BR \times DCF \qquad \textbf{Equation 6.0-1}$$

where

χ/Q = atmospheric dispersion factor (s/m^3),

BR = Breathing Rate (m^3/s), and

DCF = Dose Conversion Factor (rem/Ci)

This chapter and Appendices E and G address the recommended approach to evaluating the terms in the above equation. They are intended to be a practical guide, not an exhaustive treatise, and thus discuss these topics only to the extent needed to support a given topic in order to calculate potential consequences to receptors downwind for the DSA accident analysis. This chapter discusses the basics and Appendices E and G provide more detail for those who wants a deeper understanding. Appendix E also discusses extreme wind events, which are not required to be addressed by DOE-STD-3009-2014 but are discussed in Appendix E for evaluation of special cases. Only atmospheric (airborne) dispersion is addressed in this chapter[21], as DOE-STD-3009-2014 excludes waterborne pathways from consideration in a DSA. However, Appendix F does provide some guidance on aquatic dilution principles with respect to infrequent releases of radioactive materials into water bodies. Numerous references exist in the literature for an in-depth background on atmospheric dispersion, for example in *Workbook of Atmospheric Dispersion Estimates, An Introduction to Dispersion Modeling* ((Turner, 1994) based on Slade 1968) and the DOE Central Registry "Toolbox" code[22] guidance documents listed in the Chapter 9 References.

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[21] This chapter does not address all pathways of interest that affect the hazard categorization of nuclear facilities as determined by DOE-STD-1027-92, Chg. Notice 1, and its technical background documents from the U.S. Environmental Protection Agency and the U.S. Nuclear Regulatory Commission.

[22] Toolbox code is a term used to identify software qualified to be listed in the DOE Safety Software Central Registry (http://energy.gov/ehss/safety-software-quality-assurance-central-registry) that is used primarily for DOE safety analyses.

Section 6.1 and Appendix E: 1) provide an introduction to atmospheric dispersion; 2) discuss the key receptors associated with accident analysis; 3) identify the various meteorological parameters that are required to drive atmospheric dispersion models; 4) provide guidance on the calculation of χ/Q and on typing atmospheric turbulence into stability classes; 5) discuss the attributes of the Gaussian plume model and the various adjustments that are required to address additional atmospheric effects (dry and wet deposition, plume rise, resuspension, etc.); 6) discuss various methods of calculating concentrations of the radioactive materials at important locations of interest; and 7) provide guidance concerning the dispersion factors to use for different situations. A brief introduction on meteorological conditions associated with complex terrain is provided, along with a discussion on three-dimensional mass-consistent variable trajectory models, which are needed to accurately assess the downwind consequences from radioactive materials in such environments. Section 6.1 also reviews a number of DOE toolbox code computational models that are used in calculating transport and diffusion of radioactive materials. This section also discusses the modeling protocol for other computer programs (or codes) used for dispersion calculations that are not part of the Central Registry and the Software Quality Assurance (SQA) process needed to meet applicable DOE SQA requirements.

Section 6.2 and Appendix G address the dose calculation and describe different types of radiation and health effects they can have on the human body, its organs, and its tissues. Radiation exposures to workers and the public are to be compared to applicable standards for radiation protection to determine if impacts warrant further consideration of engineered and/or administrative controls to prevent or mitigate exposure to the worker and public.

The general approach for atmospheric dispersion and radiological consequence analysis is:

- From the accident scenario as defined by applying Chapter 3 guidance, identify parameters relevant to evaluating releases to the environment and determining consequences. These could include:
  - isotopic abundances;
  - half-lives of these isotopes;
  - decay chains and daughter ingrowth of these isotopes;
  - particle size distributions of the isotopic mix;
  - radiochemical form and properties, such as solubility;
  - dose conversion factors for the isotopes of interest;
  - locations of key receptors;
  - amount of material released in the accident;
  - heat released in a fire;
  - stack height;
  - stack inside diameter;
  - stack orientation relative to the horizon (such as upward);
  - stack emission exit temperature;
  - exit speed of effluent emitted from stack;
  - dimensions of nearby and adjacent buildings, if aerodynamic effects of buildings are to be included; and,
  - topography throughout the modeling domain, if a complex terrain model is used.
- Select the appropriate dispersion methodology, such as given in a DOE Toolbox code or manually applied in spreadsheet calculations.
- Analyze appropriate and local weather data and convert to a format for the selected methodology.

- Apply the atmospheric dispersion methodology, justifying input values as affected by the accident scenario, unique site conditions, or recommended default values from guidance documents, such as those for the DOE Toolbox codes or this chapter. Make sure that input values chosen are consistent with DOE-STD-3009-2014.
- Determine appropriate DCFs and BR for public and co-located workers.
- Calculate dose to receptors.

6.1 ATMOSPHERIC DISPERSION

This section identifies the key receptors and various meteorological parameters that are required to drive atmospheric dispersion models and it discusses the attributes of the Gaussian plume model. It also discusses various methods of calculating concentrations of radioactive materials at important locations of interest and provides guidance concerning the atmospheric dispersion factors to use for different circumstances. Appendix E provides insight into the various adjustments to the Gaussian plume model that are required to address additional atmospheric effects. These include, but are not limited to deposition and plumes generated from energetic events (detonations, deflagrations, fires).

6.1.1 INTRODUCTION TO ATMOSPHERIC DISPERSION

Figure 6-1 (Turner, 1994) illustrates the general shape of a Gaussian plume as released from a stack. The coordinate system typically used in Gaussian equations is shown, in which x is defined as the downwind direction, y is the horizontal cross-wind direction, z is vertical direction, h is stack height, and H is plume height.

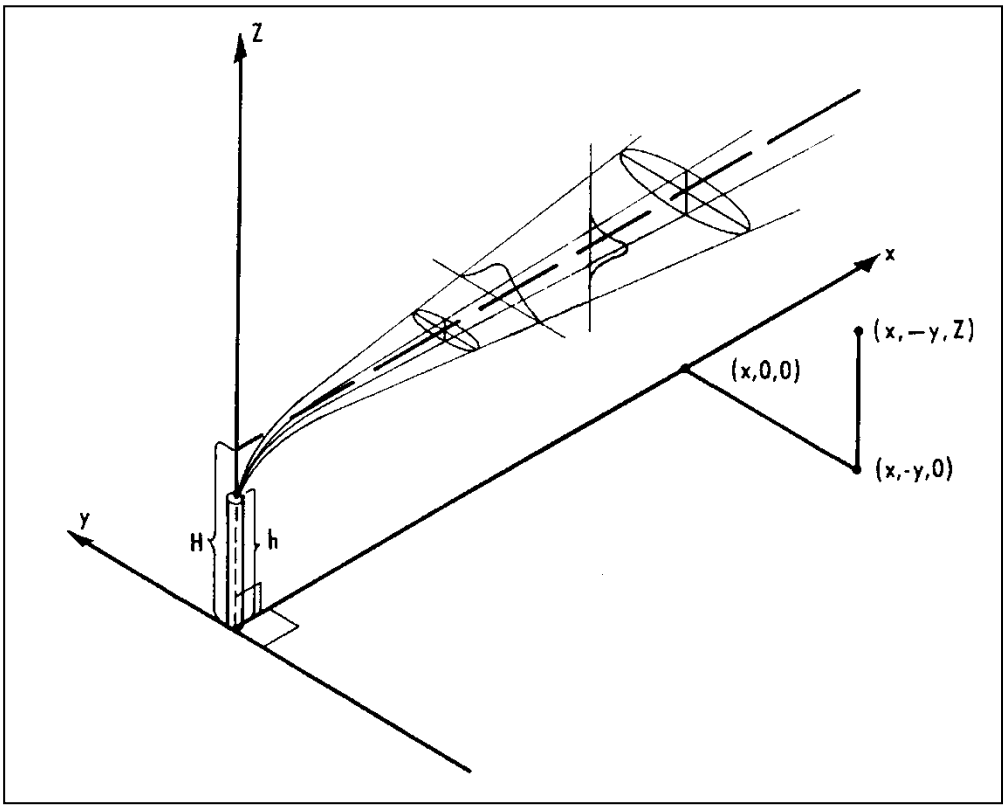

Figure 6-1. Coordinate System of Gaussian Plume.

The amount of atmospheric dispersion is usually expressed in terms of χ/Q, where

χ = the concentration of the radionuclides or toxic chemical in air at some downwind (x, y, z) location; this can be either the instantaneous concentration (Bq/m^3 or g/m^3) or the time-integrated concentration (Bq-s/m^3 or g-s/m^3), and

Q = the constant rate of radionuclide or toxic chemical release (Bq/s or g/s), if χ is the instantaneous concentration, or total source strength (Bq or g), if χ is the time integrated concentration.

For continuous neutrally-buoyant radionuclide and toxic chemical releases, the plume is diluted by the wind as it stretches the plume, and by the subsequent horizontal (lateral) and vertical diffusion, which can be reasonably approximated by a steady-state Gaussian distribution in both the crosswind (lateral) and vertical directions. As the plume moves downwind, it gets progressively larger and less concentrated due to lateral and vertical diffusion. Longitudinal diffusion (in the direction of motion) is also present but much smaller than the diluting wind and is ignored in the Gaussian plume equation. It does become important for short duration puff releases and is part of the Gaussian puff equation.

The units of χ/Q are s/m^3 whether the instantaneous or time-integrated releases are considered or whether radioactive or chemical releases are being evaluated. Thus, χ/Q is the concentration of the radionuclides or toxic chemical in air at the receptor per unit source rate, or time-integrated concentration per unit source. The actual concentration of the radionuclides or toxic chemical in air (χ at the receptor is thus the product of χ/Q and the rate of release of the radionuclides or toxic chemical (Q), as determined by the source term calculations from Chapter 5 of this Handbook.

A simplified application of the Gaussian model for a ground-level release to determine the maximum concentration at plume centerline is:

$$\frac{\chi(x, y = 0, z = 0, h = 0)}{Q} = \frac{1}{\pi u \sigma_y \sigma_z}$$ **Equation 6.1-1**

where, u is the wind speed, and σ_y, and σ_z are the standard deviations of plume dimensions in the y and z directions, which are sometimes called the half-width and half-thickness of the plume. Methods to calculate σ_y, and σ_z are given in Appendix E, Section E1.2.

Most releases considered in DSAs are continuous. For releases of a short duration (a puff), the mean wind speed acts as a transport mechanism and the turbulent diffusion in the downwind direction becomes meaningful. Short duration is generally defined as one minute or less. A puff is described by Gaussian distributions in all three dimensions (downwind or longitudinal, as well as lateral and vertical), whereas a continuous release is described by Gaussian equations in two cross-wind dimensions (lateral and vertical) and a length, determined by wind speed and duration.

6.1.2 KEY RECEPTORS

The concentrations of pollutants at selected downwind distances are estimated in order to calculate the consequences to hypothetical receptors. DOE-STD-3009-2014 identifies two generic receptors[23] to be considered in accident analyses involving atmospheric dispersion: the co-located worker (CW), and the MOI[24].

> **Co-located Worker (CW)**: A hypothetical worker located at a distance of 100 m from a facility (building perimeter) or estimated release point, defined to allow dose comparison with numerical criteria for selection of SS controls described in Chapter 2. The CW may be located at a farther distance if an elevated or buoyant radioactive plume is expected to cause a higher exposure beyond the 100 m distance. For ground level, non-buoyant releases DOE-STD-3009-2014, Section 3.2.4.2, *Radiological Dose Consequence*, specifies the CW χ/Q value as 3.5E-03 s/m^3 (based on NSRD-2015-01, *Technical Report for Calculations of Atmospheric Dispersion at Onsite Locations for Department of Energy Nuclear Facilities*).[25]

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[23] A third generic receptor, the facility worker (FW), is also considered in the DSA hazard evaluation. The FW is a worker within a facility boundary and located less than 100 m from the release point. Atmospheric dispersion is not considered for this worker.

[24] Also sometimes called the MEOI.

[25] DOE-STD-3009-2014 Section 3.2.4.2 does not specify the CW χ/Q value for elevated or buoyant releases. It does allow a value other than 3.5E-03 s/m^3, if technically justified. See Appendix E for more discussion and methods to calculate an alternative value and Section E.2 for a justification of the 3.5E-03 s/m^3 value.

MOI: A hypothetical individual representing the public, defined to allow dose comparison with an evaluation guideline for selection of SC controls described in Chapter 2. The MOI is located at the point of maximum exposure on the DOE site boundary of the facility in question (ground level release), or perhaps at some farther distance if an elevated or buoyant radioactive plume produces a higher exposure (airborne release) beyond the site boundary. Although this definition is specifically for radiological exposures, it can be extended to toxic chemical exposures as well for selection of SS controls as described in Chapter 2.

Radiological exposure is treated differently than exposure to toxic chemical emissions. For radiological exposures, the total time-integrated effective dose (primarily due to inhalation dose) is normally of interest because it is bounding for most radionuclide releases. To be conservative, the receptor may be assumed to remain in the plume centerline during the entire period of plume passage, although evaluations for mitigated analysis may consider emergency management dose-reduction measures (evacuation, sheltering). For toxic chemical exposures, on the other hand, the average, or peak, concentration during some exposure period (such as 15 minutes) is normally of greatest interest, as concentration, not *dose*, is considered for most toxic chemicals of concern. Thus, for radiological exposures, the total time-integrated release is considered, whereas for toxic chemical exposures, the source emission *rate* is considered. Some chemicals are treated in a manner similar to that of radiological exposures and is addressed further in Chapter 7.

6.1.3 METEOROLOGICAL PARAMETERS AFFECTING ATMOSPHERIC DISPERSION

If the nature of radiological and toxic chemical releases makes them neutrally buoyant, as in the release of trace amounts of very fine particulates or of gases that have a molecular weight similar to that of the atmosphere (28.97 g/mole), plume dispersion approximates a Gaussian distribution in both the crosswind (lateral) and vertical directions.

For continuous releases, the magnitude of the downwind diffusion (σ_x) is negligible in comparison with the speed of the wind. However, if the release is short duration (a puff) the mean wind speed only acts as a transport agent and the turbulent diffusion in the downwind direction becomes meaningful. Accordingly, a puff is described by Gaussian equations in all three dimensions whereas a continuous release is described by Gaussian equations in two dimensions (width and thickness) and a length determined by wind speed and release duration.

6.1.3.1 WIND SPEED, WIND DIRECTION, AND WIND DIRECTION STANDARD DEVIATIONS

Wind velocity is a vector quantity, having both magnitude and direction. Its magnitude is the wind speed. Variations in both magnitude and direction are important in dispersion.

6.1.3.1.1 WIND SPEED

The wind speed at the height of the release determines the travel time to reach a given downwind receptor and the amount of *initial* dilution from the point of release. The greater the wind speed, the more "stretched out" the plume will be and the more surrounding air will be mixed in. It is also a factor in determining the magnitude of atmospheric stability, which is discussed below. Mechanical turbulence is generated in the air when adjacent parcels of air move at different velocities, either at different speeds or in different directions; this is termed wind shear. Thus, a change in wind speed with height above the ground, or a variation in wind direction at different heights above the ground, causes mechanical turbulence. Mechanical turbulence is also generated when air interacts with some fixed object, such as the ground, described by roughness length, or with a building, described by aerodynamic effects (wake,

cavity). Short-lived radionuclides may decay appreciably if the transport time of the puff or plume to a receptor is long. The horizontal wind speed used in Gaussian models is based on the average wind speed over a selected time, usually fifteen minutes or one hour. Gaussian models are very conservative under light wind speed conditions (<1 m/s) since such conditions are too variable to be accurately approximated by a steady-state code.

6.1.3.1.2 WIND DIRECTION

The horizontal wind direction at the height of the release determines the initial direction of transport and therefore, which downwind receptors will be exposed. The horizontal wind direction used in Gaussian modeling is the average, or first moment, of a series of "instantaneous" wind direction measurements. By convention, the horizontal wind direction is 180° out of phase with the downwind or transport direction. That is, wind direction is in the "from" direction. For example, a SE wind (as termed by meteorologists) will transport the plume to the NW. For a steady-state straight-line Gaussian model, the direction of transport always remains the same in time and space, as do the wind speed, turbulence intensities, and release rate.

6.1.3.1.3 WIND DIRECTION STANDARD DEVIATIONS

Atmospheric turbulence is directly related to the variability of the instantaneous wind direction. This variability is normally expressed in terms of the standard deviation of a series of "instantaneous" wind direction measurements over a selected observation period, normally 15 minutes. The standard deviation, or second moment, of the horizontal wind direction (σ_θ) is commonly used to type atmospheric turbulence into stability classes. Some DOE sites also include the standard deviation of the vertical wind component (σ_φ) to type atmospheric turbulence, as discussed further in Section 6.1.6.

6.1.3.2 VERTICAL TEMPERATURE PROFILES

Atmospheric turbulence can also be produced by temperature gradients, especially vertical temperature gradients. The pressure of the atmosphere decreases with height. Therefore, when a parcel of air is displaced vertically, it will expand if rising or contract if sinking to adjust its pressure to that of the surrounding atmosphere. The expansion or contraction is accompanied by an adiabatic (no gain or loss of heat) temperature change. Accordingly, as a parcel rises, it cools. If the surrounding air is warmer, the parcel will be heavier than its surroundings and sink back toward its original position until it reaches equilibrium. On the other hand, if the surrounding air is cooler, the parcel will be lighter and continue to move upward and its vertical motion is enhanced. Similarly, if the air parcel sinks, it warms up as it contracts. If the surrounding air is cooler, the parcel will be lighter and rise back toward its original position until it reaches equilibrium. However, if the surrounding air is warmer, the parcel will be heavier and continue to sink. Thus, turbulence is suppressed if the temperature profile of the air, termed the lapse rate, is less than adiabatic (subadiabatic), and enhanced if greater than adiabatic (superadiabatic). The dry adiabatic lapse rate near ground is about -9.8 °C/km (-5.4 °F/1,000 feet), while the moist adiabatic lapse rate, which depends on temperature, is typically about -5.8 °C/km (-3.2 °F/1,000 feet); the difference is due to heat required to overcome latent heat of the moisture in the air parcel (Wallace and Hobbs, 1977).

The atmospheric layer near the ground is termed the mixed layer, as this is where atmospheric turbulence is most common. During daylight, the ground heats up, warming the air near the surface through convective eddy transport. The lapse rate near the surface thus becomes superadiabatic and positive buoyancy forces enhance any existing mechanical turbulence caused by ground roughness or wind shear. At night, the ground cools due to release of long-wave radiation, causing the air near the surface to cool, and the lapse rate becomes subadiabatic and frequently inverted, suppressing much of the existing

mechanical turbulence. At greater heights, a few hundred to a few thousand meters in altitude, the lapse rate may change. It is common for a turbulent lower atmosphere to be capped by a lapse rate that is subadiabatic so that turbulent eddies rising from below are suppressed. Vertical plume expansion is thus limited, reflecting off the top of the mixed layer (as well as off the ground).

6.1.3.3 PRECIPITATION

With regard to precipitation scavenging (rainout, snowout, hailout), the rate of precipitation is needed as an input to models that address this atmospheric phenomenon. Rainout can cause major local deposition of radionuclides leading to radioactive "hot spots" at locations that receive rainfall. DOE-STD-3009-2014 does not require the consideration of precipitation scavenging in DSAs.

6.1.4 CHARACTERIZATION OF METEOROLOGICAL AND SITE DATA

The application domain that atmospheric dispersion codes approximate establishes the types of meteorological data needed to drive such codes. The choice of code that the analyst uses to solve a particular application may be limited by the availability of meteorological data. This subsection gives a brief discussion of various meteorological data sets often used as input to atmospheric dispersion codes.

6.1.4.1 PERSISTENCE

The simplest models assume that constant weather conditions prevail during the accident duration, whether unfavorable conditions or typical conditions. DOE-STD-3009-2014 Section 3.2.4.2 states that if representative meteorological data are not available, stability Class F and 1.0 m/s wind speed may be used for unfavorable radiological dispersion consistent with NRC's and DOE's long-standing practice as this approximates the 95th percentile dispersion condition. For perspective, Class D stability and 4.5 m/s wind speed are used for "typical" conditions.

The choice of wind speed depends on the guidance document being followed. For sites in deep valleys where a high frequency of low wind speeds occur (such as Y12), Class F stability and wind speeds less than 1.0 m/s may possibly apply. For many models, a meteorological data couplet of wind speed and stability class and the distance to the receptor are the only inputs that are needed, as the release rate and atmospheric conditions are time-invariant in Gaussian models.

6.1.4.2 JOINT FREQUENCY DISTRIBUTION (JFD)

The JFD required by many atmospheric dispersion codes is the joint distribution of wind speed according to wind direction and stability class. The JFD is organized into a matrix that gives the percent of the time of each condition for specified numbers of wind speed groups and stability class for each of the 16 wind direction sectors (N, NNE, NE, … NNW).

This distribution is based on an extended period of meteorological observations in order to establish temporal representativeness, five or more years, if available. If the climate is changing, the latest five to ten years (DOE-STD-3009-2014) should be used. The larger number of years smooths out the decadal climatic variations. The wind speed data are sorted into bins, such as 0 - 1 m/s, 1 - 2 m/s, 2 - 4 m/s, …. Since calm wind speeds cannot be used in a Gaussian plume model, the calms are redistributed into the lowest wind speed class based on the frequency of wind directions in the lowest two wind speed classes. The choice of bins may be dictated by the code but for some codes (such as GENII) the user chooses the number of wind speed bins and the ranges of these bins. These would depend upon the wind conditions at the DOE site. The number of frequency bins in this matrix can reach several hundred. For example, if

six stability classes (A–F) and six wind speed bins are chosen, the total number of frequencies would be 6 × 6 × 16 = 576. However, not all bins will be populated as stronger winds cannot simultaneously occur with Class A and Class F stability class conditions.

A utility computer program is usually needed to generate a JFD, especially if several years of hourly observations are being used. When a joint frequency matrix is being generated, the definition of wind direction used in the code should be kept in mind. In meteorology, wind direction has traditionally been defined as the direction from which the wind blows, which is of interest to weather forecasters. However, most computer models for dispersion and consequence applications, such as those in the DOE Central Registry, use wind direction to mean the direction toward which the wind blows. The downwind (transport) direction is always 180 degrees out of phase with the direction that a meteorologist uses. Thus, the analyst needs to be aware the wind direction-sector orientation of the particular code being applied.

Temporal representativeness simply means that the data base is sufficiently large to have captured a reasonable number of climatic anomalies such that an additional year of data will not substantively affect radiological and toxic chemical consequence calculations.

6.1.4.3 FULL DATA SET SAMPLING

An alternative to a JFD matrix that is used by MACCS2 and HOTSPOT is to use the data from all 8760 hours in a year to achieve the maximum temporal representativeness and therefore highest accuracy in calculating the overall site 95th percentile consequences or the sector-dependent 99.5th percentile consequences.

6.1.4.4 TREATMENT OF CALM AND VARIABLE WINDS

Wind speeds that are below the threshold wind speed of the mechanical or sonic anemometer are generally set equal to the rated threshold wind speed or wind direction of a mechanical or sonic anemometer, whichever is lower. The threshold wind speed and wind direction of a mechanical anemometer is usually 0.5 m/s. Sonic anemometers have somewhat lower threshold wind capabilities and thus can measure even lower wind speeds as they infer wind speed from differences in the speed of sound and usually have a threshold wind speed of 0.3 m/s. ANSI/ANS-3.11-2015, *American National Standard for Determining Meteorological Information at Nuclear Facilities*, defines a calm as, “any wind speed below the starting threshold of the wind speed or direction sensor; or any wind speed below that which is appropriate for input into plume models, whichever is greater. In the US, calm is typically defined as any speed less than 1 mph”. Similarly, EPA recommends using a wind speed of 1 mi/hr (0.5 m/s) for a “calm” wind, and cautions against overly conservative model predictions with wind speeds less than 1 m/s (EPA, 2000). Moreover, NSRD-2015-TD01, “Technical Report for Calculations of Atmospheric Dispersion at Onsite Locations for DOE Facilities” (NRSD-2015), cautions on the limitations of Gaussian dispersion modeling, as this type of model has the tendency to overpredict concentrations at the lower end of a range of conservative wind speeds; especially calm wind speeds. This important consideration is treated in more detail in Appendix E Section E1.3.

Option 2 of DOE-STD-3009-2014, Section 3.2.4.2, specifies a minimum wind speed of 1 m/s. However, MACCS2 replaces wind speeds of less than 0.5 m/s with 0.5 m/s and this is acceptable as this is a fixed part of the code. If a site’s conditions have a high incidence of low wind speeds the site may want to consider software that addresses this condition. Other DOE Toolbox codes, such as Hotspot and GENII, incorporate a low wind speed algorithm (e.g., the G stability option).

6.1.5 METEOROLOGICAL DATA ADEQUACY FOR SAFETY ANALYSIS

The results from atmospheric dispersion codes can be no better than the input data and the conditions under which it is applied. The accuracy of the codes is also limited by the approximations inherent in the models, with results being more reliable nearby the release point than farther away, within the application's domain. Inaccuracies in the meteorological data tend to be amplified with increasing transport distance.

Generally, data need to be input with the full accuracy of the measurements and rounding should be only performed on the final results. Even the most comprehensive atmospheric dispersion codes in use today will likely be uncertain by a factor of two or more, even relatively close to the release point for flat terrain topography. (DOE-STD-5506-2007 estimates a factor of four uncertainty). Therefore, one-digit accuracy, or at most two digits, is all that should be reported in the analyst's results, except perhaps for purposes of comparisons of similar results. Since there are so many uncertainties in the input data streams and within the models, the following phrase gives some perspective: "The mantissa is meaningless, while the exponent is everything."

The minimal set of meteorological data needed to run an atmospheric dispersion code that requires observational data would be at least one year of wind speed, wind direction, and an indicator of stability class. However, one year of data may not prove to be very temporally representative, as notable climatic anomalies frequently occur on as little as an annual basis (El Niño, La Niña), and decadal climatic anomalies have been noted.

NRC Regulatory Guide 1.194 , *Atmospheric Relative Concentrations for Control Room Radiological Habitability Assessments at Nuclear Power Plants*, indicates that the size of the data set used in assessments should be sufficiently large such that it is representative of long-term meteorological trends at the site in question. In this Regulatory Guide, NRC staff considered 5 years of hourly observations to be representative of long-term trends at most sites. However, the Guide also states "With sufficient justification of its representativeness, however, the minimum meteorological data set is one complete year, including all four seasons, of hourly observations."

A basic rule of thumb is to use at least five years of meteorological data to ensure that temporal representativeness would not be compromised. If a larger data base is available, it should be used, even if the resulting atmospheric dispersion estimates change from prior analyses. Moreover, DOE-STD-3009-2014 specifies that the latest five years of data should be used and recommends that the 95th or 99.5th percentile value should be used. If five years of data are not available, justification for using a shorter period needs to be provided. A reanalysis is needed only every ten years, as the average of meteorological parameters change relatively slowly over time.

The indicator of stability class would be either temperature gradient (χT_z) or wind direction (σ_θ) variations. Many models also require measurements of precipitation, temperature, and humidity. Hourly-average data from a meteorological station near the DOE site, giving spatial representativeness, are typically required by Gaussian plume models.

6.1.6 ATMOSPHERIC STABILITY CLASSES

Atmospheric dispersion is so complex and turbulence is so random and chaotic, formulas must be derived from empirical observation. One method defines distinct atmospheric stability classes and associates a magnitude of lateral and vertical diffusion with each stability class as a function of downwind distance only. Although these computations provide only a rough approximation to reality, they have proven extremely useful and are still in use, although treatments that are more accurate are available. The most common measurements employed in typing stability class are wind direction variability and vertical temperature gradients. The wind direction variability provides the best approximation of mechanical turbulence and the vertical temperature gradient provides the best approximation of the buoyancy component. The following subsections provide some definitions associated with stability class and the methods to type it in order to approximate the turbulence intensities that drive atmospheric dispersion. From this, σ_y, and σ_z in Equation 6.1-1can be calculated (Appendix E, Section E1.2).

6.1.6.1 DEFINITIONS OF STABILITY CLASSES

The rate at which turbulence diffuses radioactive and toxic chemical emissions depends upon the stability of the atmosphere. Seven stability classes (the Pasquill-Gifford-Turner classes) have been defined. These classes, with their relation to temperature gradient, and the conditions of occurrence, are defined below. The first six are the Pasquill-Gifford (P-G) classes and the seventh was added for fumigation conditions.

A: Extremely Unstable (strong superadiabatic). Normally occurs during bright sunshine with relatively low wind speed (< 3 m/s).

B: Moderately Unstable (moderate superadiabatic). Normally occurs during conditions that range from bright sunshine, with wind speeds in the 3 to 5 m/s range, to dim sunshine, with wind speeds < 2 m/s.

C: Slightly Unstable (slight superadiabatic). Normally occurs during conditions that range from bright sunshine with wind speeds in the 5 to 6 m/s range, to dim sunshine with wind speed in the 2 to 3 m/s range.

D: Neutral (adiabatic). Normally occurs with moderate to dim sunshine, cloudy conditions, and at night, with wind speeds > 3 m/s. It also occurs with very strong wind speeds on either sunny or cloudy days. It usually is the most frequent of the stability classes.

E: Slightly Stable (slight subadiabatic with or without inversion). Normally occurs at night or early morning with some cloud cover and with wind speeds in 2 to 5 m/s range.

F: Moderately Stable (moderate subadiabatic with inversion). Normally occurs at night or early morning with little cloud cover and with relatively low wind speeds (< 3 m/s).

G: Extremely Stable (strong subadiabatic with inversion)[26]. Normally occurs at night or early morning with very light to nearly zero wind speed (calm wind conditions).

[26] The NRC uses Class G in its licensing but DOE does not. In the RSAC code used at Idaho National Laboratory, an additional class, referred to as “class F fumigation”, is introduced. It is similar to class G but in the RSAC code is distinct from G. HOTSPOT and GENII both include Class G stability.

G stability class, as well as the F stability class, is associated with inversion breakup fumigation conditions, occurring in early morning, in which an elevated plume is rapidly forced to the ground. Due to the stable conditions (slow lateral and vertical diffusion) and the low wind speed (slow dilution), the plume concentrations that are rapidly brought to the ground can be high. Fumigation represents the worst case scenario for near-field immersion doses associated with elevated releases.

Unstable conditions result in rapid-spreading lateral and vertical diffusion of pollutants (wide plumes), whereas stable conditions result in slow-spreading lateral and vertical diffusion (narrow plumes).

Although Class A stability is not rare, it is not as common as Classes B through F. Class D is the most common stability class because of the large number of combinations of meteorological conditions that can result in Class D stability. For example, high-wind conditions and/or cloudy conditions during the day or at night are normally Class D. During periods of extended rainfall and overcast conditions, as many as 100 consecutive hours of Class D stability have been recorded. Classes E and F most commonly occur at night. Class G is less common and it is often ignored in computer models based on the Gaussian equations. Inversion breakup fumigation (Class G) occurs when a very stable atmosphere becomes a very unstable atmosphere in response to early morning heating. An elevated plume can be quickly brought down to the surface through the fumigation depth.

6.1.6.2 METHODS OF CALCULATING STABILITY CLASSES

Many schemes have been proposed for determining stability class from measured meteorological parameters. The conditions listed above are dependent on wind speed and amount of incoming solar radiation. These stability class definitions are not practical for many DOE sites because the amount of opaque cloud cover is a visually observed condition and not normally recorded by automated weather instrumentation. In addition, opaque cloud cover is somewhat subjective, varying from observer to observer. Alternative methods have therefore been developed based on measured data.

Several methods exist to convert measured or observed meteorological data into atmospheric stability class data. Two methods are recommended given their regulatory support by the NRC and EPA and their use across DOE sites based on available meteorological data. Note that the NRC guidance for stability classification extends the original Pasquill-Gifford (P-G) scheme by subdividing P-G Class F to create a seventh stability class (class G) for extremely stable condition. In contrast, the EPA guidance specifies only the original six stability classes. Two additional stability classification techniques that are less commonly used are presented in Appendix E, Section E.5. The implications for atmospheric transport and diffusion modeling are addressed below.

The method that is prescribed by the NRC for supporting licensing of nuclear power plants makes use of measurements of vertical temperature difference (ΔT_z) to determine atmospheric stability as shown in Table 6-1 (NRC, 1982). In this method, ΔT_z is expressed in terms of the vertical temperature difference over a 100-meter layer of the atmosphere (termed ΔT_{100m}), with the lowest measurement 10-m above the ground. Typically, ΔT_{100m} is determined by doubling the difference in temperature measurements at 60 m and 10 m, which are common temperature measurement heights at DOE sites.

Table 6-1. Classification of Atmospheric Stability Based on Vertical Temperature Difference.

Stability Classification	Stability Class	Ambient Temperature Change with Height (°C/100 m)
Extremely unstable	A	$\Delta T_{100m} \leq -1.9$
Moderately unstable	B	$-1.9 < \Delta T_{100m} \leq -1.7$
Slightly unstable	C	$-1.7 < \Delta T_{100m} \leq -1.5$
Neutral	D	$-1.5 < \Delta T_{100m} \leq -0.5$
Slightly stable	E	$-0.5 < \Delta T_{100m} \leq 1.5$
Moderately stable	F	$1.5 < \Delta T_{100m} \leq 4.0$
Extremely stable	G	$\Delta T_{100m} > 4.0$

Example: If the temperature at 10 m was 10°C and at 60 m it was 9.5°C, the stability would be Class D.

DOE site meteorologists have observed that turbulence typing based on boundary layer temperature gradients tend to produce a distribution of categories that is skewed toward the strongly stable (F and G) and strongly unstable (A and B) categories; especially if the upper measurement level is lower than 60 m.

A method recommended by the EPA calculates the stability in a two-step process based on turbulence measurements. The first step makes an initial estimate and the second makes a correction to the initial estimate.

The initial categorization is based on the standard deviation of wind direction fluctuations in the azimuth (horizontal) plane (σ_θ) as shown in Table 6-2 (EPA, 1987).

Table 6-2. Initial Estimates of Stability Class, EPA Method.

Stability Class	Standard Deviation of Wind Direction, σ_θ
A	$22.5° \leq \sigma_\theta$
B	$17.5° \leq \sigma_\theta < 22.5°$
C	$12.5° \leq \sigma_\theta < 17.5°$
D	$7.5° \leq \sigma_\theta < 12.5°$
E	$3.8° \leq \sigma_\theta < 7.5°$
F	$\sigma_\theta < 3.8°$

Note that EPA does not consider G stability as a valid stability class. The final categorization is then made by combining this initial estimate with the wind speed and time, specifically whether it is “day” or “night”, as shown in Table 6-3. “Day” is defined here as being the period between one hour after sunrise and one hour before sunset. The remainder of the time is defined as “night”. For some DOE sites that are located nearby large bodies of water and subject to sea breezes and lake breezes (Brookhaven National Laboratory, Argonne National Laboratory), it may be necessary to adjust the definition of “day” to account for the later onset of more stable conditions during morning and afternoon lake breeze and sea breeze conditions.

Table 6-3. Final Estimates of Stability Class, EPA Method.

Time	Initial Estimate	Wind Speed, WS (m/s)	Final Estimate
Daytime	A	WS < 3	A
		3 ≤ WS < 4	B
		4 ≤ WS < 6	C
		6 ≤ WS	D
	B	WS < 4	B
		4 ≤ WS < 6	C
		6 ≤ WS	D
	C	WS < 6	C
		6 ≤ WS	D
	D, E, or F	ANY	D
Nighttime	A	WS < 2.9	F
		2.9 ≤ WS < 3.6	E
		3.6 ≤ WS	D
	B	WS < 2.4	F
		2.4 ≤ WS < 3.0	E
		3.0 ≤ WS	D
	C	WS < 2.4	E
		2.4 ≤ WS	D
	D	ANY	D
	E	WS < 5.0	E
		5.0 ≤ WS	D
	F	WS < 3.0	F
		3.0 ≤ WS < 5.0	E
		5.0 ≤ WS	D

Example: If the value of σ_θ was measured to be 3.0°, the initial classification would be Class F. Then if the wind speed was measured to be 4 m/s and it was night, the final estimate would be Class E.

6.1.7 GAUSSIAN PLUME WIDTHS AND DEPTHS

Once the stability class has been determined for a given weather scenario, the plume widths and depths (σ_y and σ_z) are estimated in order to calculate χ/Q. This is needed for each hour of the year for five years or more, to be compliant with DOE-STD-3009-2014, and for selected distances from the point of release, out to the MOI, or beyond if the plume is lofted. Appendix Section E1.2 discusses the various methods of calculating σ_y and σ_z. The methods are dependent on distance and terrain roughness.

> Example: If the stability class is determined to be E, and the Tadmor-Gur method is chosen, the values of σ_y and σ_z at 1,000 m would be calculated from $\sigma = a\,x^b$, where $a_y = 0.1046$, $b_y = 0.9031$, $a_z = 0.4$, and $b_z = 0.6021$. This gives $\sigma_y = 0.1046\times1000^{0.9031} = 53.6$ m and $\sigma_z = 0.4\times1000^{0.6021} = 25.6$ m. The width (σ_y) is then adjusted by the plume meander factor and the depth (σ_z) by the surface roughness factor. For a one hour plume duration and a 10 minute time base, the plume meander factor would be $(60\text{ min}/10\text{ min})^{0.2} = 1.43$, yielding $\sigma_y = 76.7$ m. For a surface roughness of 100 cm (such as in a forested region), the roughness factor would be 2.02, yielding $\sigma_z = 51.7$ m.

Calculations such as in this example, are performed within the various dispersion codes, such as MACCS2 (discussed in Section 6.1.9). They can also be calculated manually using a spreadsheet but this is normally done only for spot checking and scoping calculations.

6.1.8 TYPICAL AND UNFAVORABLE DISPERSION CONDITIONS

In calculating plume concentrations, or consequences to the receptor, both "typical" and "unfavorable" dispersion conditions are of special interest in accident analyses. "Typical" would not be used to establish safety SSCs in a DSA but it is useful for Safety Goal comparison, if over the EG (see Section 6.1.11).

Typical Dispersion Conditions: The median (50th percentile), the mean (average), or the mode (peak) of a distribution could all be considered as representative of "typical". However, the median is the most meaningful for plume dispersion, for several reasons. It is not heavily influenced by outliers (abnormally small or large values), as is the mean. For a bimodal distribution, which is common to dispersion, the mean may fall between the peaks (modes) of the distribution and thus be comparatively infrequent, which could not be considered "typical". The median could also be atypical in this sense but it, at least, has a relevant meaning. In addition, if mode were chosen as "typical", a bimodal distribution could give two valid choices if the peaks are nearly as large.

Unfavorable Dispersion Conditions: This is normally taken to be the overall site 95th percentile dispersion of the full meteorological data set for at least one year, for which the consequences are smaller 95% of the time and larger 5% of the time. Other dispersion conditions are sometimes used for "unfavorable", such as "worst case", "near-worst case", or specific constant-weather conditions, such as Class F stability and 1.0 m/s wind speed. Near-worst-case conditions, which are most likely G stability class and nearly calm winds are extremely rare and would be overly conservative for most applications. (True "worst case" is a single value, that is, the maximum value, obtained only once in the period of interest.)

For elevated releases, the above rules of thumb would not apply as they would depend on the release height. Also, the amount of atmospheric dispersion corresponding to 50th or 95th percentile weather depends upon the nature of the release. If the release is a trace constituent, it can be treated with a

Gaussian plume or puff model, depending upon the duration of the release. If it is a dense or heavy gas (discussed in Chapter 7), it is treated with a heavy-gas model that both limits vertical dispersion due to slumping, while simultaneously entraining ambient air through the sides of the plume. The amount of dispersion for the 50th or 95th percentile conditions would likely be different for a heavy gas model.

All radioactive plumes should be considered as trace-amount releases. They can be analyzed with the Gaussian plume model, as well as with more sophisticated models discussed in Appendix E1.6. Likewise, if a small quantity of a toxic chemical is spilled or released in a fire or explosion, the resultant plume can be approximated with the Gaussian plume model, as long as the additional plume buoyancy and explosion overpressures are appropriately addressed[27]. For toxic chemicals, however, other complicating factors need to be considered, such as chemical reactions within the plume, and source term determinants, such as evaporation rate, aerosolization rate, subcooling, and superheating; all of which are covered in Chapter 7.

6.1.9 DOE CENTRAL REGISTRY OF RADIOLOGICAL DISPERSION AND CONSEQUENCE ANALYSIS CODES

Since 2004, a collection of computer codes, including those for performing atmospheric dispersion and radiological or chemical consequence analyses, have been designated as Toolbox codes in the DOE Safety Software Central Registry (CR) and managed by the DOE Office of Quality Assurance (AU-33) . While these models have widespread use and have accumulated considerable levels of analyst understanding, they still warrant careful consideration in the preparation of inputs and assumptions to ensure that the resulting outputs are technically defensible and consistent with expectations of the analysis, and that resulting safety control sets are adequate, robust and implementable. Accordingly, every Toolbox model needs to be independently evaluated according to the SQA principles in DOE O 414.1D and DOE G 414.1-4[28], *Safety Software Guide for use with 10 CFR 830 Subpart A, Quality Assurance Requirement*[29]. Modeling techniques inherent in the toolbox software and guidance for their use, including input requirements, are discussed below. Note that model evaluation is not one of the work activities to be considered per DOE Order 414.1D, Attachment 4 nor discussed in the G 414.1-4.

Of the eight toolbox codes that comprise the DOE Safety Software Central Registry, three are applicable to radiological dispersion and consequence analysis applications (GENII, MACCS2, and HotSpot) and two are applicable to chemical dispersion and consequence analysis applications (ALOHA and EPIcode). The other toolbox codes address fires (CFAST), in-facility transport (MELCOR) and biological uptake (IMBA). The three radiological dispersion computer models are listed in Table 6-4 along with their respective developing organization, toolbox version, the year designated for the Central Registry, and current version supported by their developer. Additional information on the DOE Safety Software Central Registry and individual dispersion and consequence analysis computer models is available through the website http://energy.gov/ehss/safety-software-quality-assurance-central-registry.

Inclusion of a code into the DOE CR provides DOE users the assurance that the SQA level is adequate for safety analysis applications along with implementation of applicable site-specific SQA requirements per site's quality assurance program (QAP) (e,g, site acceptance testing, user training, configuration control, error reporting.). For six of the eight Toolbox codes, , the gap analysis report, evaluating individual software for specified SQA requirements, and the associated code guidance report are specific to the version of the code at the time the software was designated as Toolbox code in the CR. If another version

[27] An example is using the Option 3 modeling as described in the DOE-STD-3009-2014, Section 3.1.4.2.
[28] SQA principles are discussed more fully in Section 3.5.
[29] The guide was written for O414.1C and is currently being revised to conform to DOE O 414.1D.

of the computer code is being considered for use, the DOE contractor is responsible for determining that the quality assurance level of the software meets applicable DOE requirements.

Table 6-4. Computer Models in DOE Central Registry for Radiological Dispersion and Consequence Analysis . (Content shown is current as of May 2015)

Computer Code	Lead /Developing Organization	Version/ Year Designated for the Toolbox	Current Version Supported by the Developer
GENII	Bruce Napier / Pacific Northwest National Laboratory	V1.485 / 2004 V2.10.1 / 2013	V2.10.1
HotSpot	Steve Homann / Lawrence Livermore National Laboratory	V2.07.1 / 2010	V3.01
MACCS2	Nate Bixler / Sandia National Laboratory	V1.13.1 / 2004	WinMACCS V3.7; MACCS2 V2.6.0

For the most part, codes in the Central Registry were developed outside of DOE [such as in the private sector or other Federal agencies (NOAA, NRC, or EPA)]. Access to the toolbox codes or their use is subject to agreements, conditions and restrictions established by the code owners or Federal agencies. The CR is currently manged by the Office of Quality Assurance (AU-33) within EHSS and the focus of AU-33 is to work with the code developers/owners to have the Toolbox codes updated and maintained following SQA provisions of applicable national consensus standards such as ANSI/ASME NQA-1 which is the preferred standard cited in DOE O 414.1D for safety software.

In the preface to the DOE Central Registry, DOE states that the Chief Health, Safety and Security Officer (DOE/HS-1, which is currently the AU-1 organization) is responsible for managing the Safety Software Central Registry. However, the toolbox code owners are responsible for ensuring that the codes are maintained in accordance with established DOE O 414.1D requirements and DOE G 414.1-4 guidance.

As stated on the DOE/AU website, use of the Central Registry toolbox codes is not mandatory. Of the three options given in DOE-STD-3009-2014 for radiological dispersion analysis only option 2 requires the use of a toolbox code. However, using the toolbox codes offers a number of advantages to DOE and its contractors. Some of these advantages include:

- The evaluation performed provides valuable information on the code regarding application of SQA requirements;
- The evaluation generally extends beyond the DOE safety software quality assurance criteria to the review of the code's capability to properly perform safety basis calculations;
- The DOE-specific guidance documents identify limitations and vulnerabilities not readily found in other code documentation;
- Due to the established pedigree, quality assurance assessments of the toolbox code by the users (DOE personnel and site contractors) may be reduced in scope; and,
- Increased user base and experience across DOE complex.

ALOHA, EPIcode, GENII, MELCOR, CFAST and MACCS2 were the original six computer codes designated for the DOE Central Registry in 2003, and each code's SQA gap analysis and code usage guidance documents were published in 2004. The gap analyses for these six codes were completed before issuance of DOE O 414.1C, *Quality Assurance*, and the safety software guidance, DOE G 414.1-4[30]. The two documents provided necessary framework for the evolving DOE requirements for safety software. With the release of DOE O 414.1C and DOE G 414.1-4, and subsequently DOE O 414.1D, *Quality Assurance*, the safety software requirements were clearly identified (Attachment 4 to the respective Orders) and guidance for meeting the requirements provided. DOE O 414.1D was issued April 25, 2011, and the Guide DOE G 414.1-4 are available through the DOE Directives Web site at http://www.directives.doe.gov/. The guide was written for DOE O 414.1C and is currently being revised to conform to DOE O 414.1D.

HotSpot V2.07.01 was added to the CR in 2010 after a detailed SQA evaluation that determined that the HotSpot SQA program and associated documentation, with some modifications, met the the safety SQA requirements of the DOE O 414.1D. With the available SQA documentation, the necessity of a separate guidance document was not established. HotSpot has been recently upgraded to version 3.01 and further revision to the code is underway following which the code developer intends to request an evaluation by DOE/AU-33.

More detailed discussions of the capabilities of MACCS2, GENII, and HotSpot are given below. These cover available toolbox atmospheric transport and diffusion models for radiological analysis. The toolbox models for chemical consequence analysis, ALOHA and EPIcode, are covered in Chapter 7. Additional supported codes (e.g. RASCAL, NARAC, RSAC8, HYRAD) should be evaluated on a case-by-case basis as to their applicability to the safety analysis that is undertaken. Should the analyst select any of these other codes, a dispersion modeling protocol (Section 6.1.11) needs to be developed and approved by DOE.

The three radiological toolbox codes listed in Table 6-4 are briefly discussed below. The toolbox version of these codes is available through the Radiation Safety Information Computational Center (RSICC).

Table 6-5 summarizes key features of the toolbox software and serves as a roadmap to the guidance given in this Handbook with respect to radiological dispersion analysis. The far-right column shows the section in the Handbook where the reader can go for detailed information on the topic when applicable.

[30] DOE O 414C, and its supporting Safety Software Guide, were approved 6-17-05.

Table 6-5. Summary Guidance on the Use of Computer Models in DOE Central Registry for Radiological Dispersion Analysis.

Model Feature	GENII	HotSpot	MACCS2	Guidance
Prescriptive Meteorology Capability	Not readily available as an option	User-defined wind speed and stability class can be input via one of the meteorological input modes	User-defined wind speed and stability class can be input via one of the meteorological input modes	Generally has been used for modeling dispersion for a high wind event. Another example is that stability class F and 1.0 m/s wind speed may be used when site specific hourly meteorological data are not available.
Plume Transport with Hourly Meteorological Data	One continuous plume generated for each hour based on constant wind direction, wind speed and stability class	One continuous plume generated for each hour based on constant wind direction, wind speed and stability class	For each source term, one continuous plume generated for each hour with constant wind direction, but wind speed and stability class changing after each hour of transport; up to 4 plumes can be used to transport and disperse 4 distinct source terms	Both the GENII2/HotSpot approach and MACCS2 approach are compliant with DOE-STD-3009.
Years of Meteorological Data	Up to ten years in single code execution	Up to five years in single code execution	One year per code execution – mean value of 95th or 99,5th percentile χ/Q from all executions typically determined	Five years is recommended (DOE-STD-3009-2014, Section 3.2.4.2).
95th and 99.5th Percentile Output for a Given Distance Based on Statistical Sampling of Meteorological Data	For each wind direction sector, considering only plumes traveling in the given sector	From overall cumulative probability distribution from all directions combined	From overall cumulative probability distribution from all directions combined	The approach of HotSpot/MACCS2 is conservative and accepted by DOE-STD-3009 even thought not fully compliant with NRC RG 1.145. Determining the maximum sector result from GENII2 is a conservative approach with respect to DOE-STD-3009.

Model Feature	GENII	HotSpot	MACCS2	Guidance
Wind Speed Profile	i) Reference height for meteorological data is an input value in first line of meteorological input data file ii) Wind speed is adjusted for release heights that differ from reference height iii) Release heights less than 12 m are modeled using 10-m wind speed iv) Surface wind speed is used together with roughness length (z_0) input in meteorological data file for determining friction velocity (u)	i) Default reference height for meteorological data is 10 m, but the user may change it. ii) Wind speed is adjusted for release heights that differ from reference height.	i) Reference height for meteorological data is always 10 m ii) Wind speed is not adjusted for release heights that differ from reference height	The 10-m wind speed is recommended for ground level releases. For elevated releases above 10 m, adjustment of the wind speed is standard practice (HotSpot, GENII2); no adjustment is conservative (MACCS2).
Treatment of Calms	User specifies minimum wind speed value (any wind speed values in meteorological data file less than minimum value is reset to minimum value)	Software resets any wind speed values in meteorological data file less than 0.1 m/s to 0.1 m/s	Software resets any wind speed values in meteorological data file less than 0.5 m/s to 0.5 m/s	Specifying a minimum wind speed of 1.0 m/s is recommended (DOE-STD-3009-2014, Section 3.2.4.2).
Dispersion Coefficient Sets	• Eimutis and Konicek (NRC) • Pasquill-Gifford (EPA) • Briggs Open Country • Briggs Urban	• Briggs Open Country • Briggs Urban	• Tadmor-Gur • Briggs Open Country • Eimutis and Konicek (NRC) • Briggs Urban	Briggs Urban set not recommended. Tadmor-Gur not recommended for distances less than 500 m. The toolbox version of MACCS2 has a lookup table error which may limit which dispersion coefficients can be used. See Section E.1.2.

Model Feature	GENII	HotSpot	MACCS2	Guidance
G Stability Class	i) Modeled explicitly with Eimutis and Konicek (NRC) set of dispersion coefficients ii) Modeled as F stability class for other sets of dispersion coefficients	i) Vertical dispersion modeled as F stability class ii) Modeling of horizontal dispersion specified by user to be equivalent modeled as any stability class in range of A through F	Modeled as F stability class	Modeling G stability class as F stability class is recommended. Experiments have shown that plume meander under class G yields dispersion conditons that are no more conservative than under Class F.
Adjustment of horizontal dispersion coefficient (σ_y) for plume meander	No adjustment currently modeled	• Averaging time method	• Averaging time method • NRC method	The averaging time method is recommended; no adjustment is conservative.
Adjustment of vertical dispersion coefficient (σ_z) for surface roughness (z_o) effects	No adjustment (User enters z_o value in meteorological data file that is used to define the wind speed profile and calculate the deposition velocity)	No adjustment	User enters roughness adjustment factor	Equation E-9 or either Equation E-10 or E-11 of Appendix E is recommended together with one of the methods discussed to determine z_o; no adjustment is conservative for ground-level non-buoyant releases
Adjustment of initial values (at source) for σ_y and σ_z for building wake effects	User inputs building dimensions and software determines initial σ_y and σ_z values	User inputs building dimensions and software determines initial σ_y and σ_z values	User inputs initial values for σ_y and σ_z	Increased dispersion from building wake effects should only be used for ground-level releases. No other adjustments should be made to the dispersion coefficients for plume meander or surface roughness effects. Ignoring building wake dispersion is generally more conservative. Option 2 in DOE-STD-3009-2014 does not allow for crediting of building wake factors
Stack Release	User enters effective release height	User enters effective release height	User enters effective release height	The use plume rise equations in Appendix E is recommended to determine effective release height taking into account stack-tip downwash and aerodynamic entrainment effects of buildings. Assuming ground release is generally more conservative.

Model Feature	GENII	HotSpot	MACCS2	Guidance
Plume Buoyancy	Plume rise model from stack available as an option. Not recommended for fire-release modeling.	• Stack plume rise model • Pool-fire plume rise model (open field)	Plume rise model from stack available as an option.	The three models employ similar models for plume rise from a stack as long as the stack meets GEP criteria. The HotSpot pool fire model is only applicable with an open field release. When using MACCS2 to model fires, the guidance of this Handbook should be followed, including inputting the height of the tallest co-located structure to account for building entrainment that can inhibit plume rise. Ignoring buoyant plume rise is conservative.
Deposition Velocity for Respirable Source Term	Software determines value for each meteorological sample using other input data and algorithms in the model	User enters value	User enters value single value	The GENII2 deposition velocity model is approved for safety analysis. When GENII2 is not used for the dispersion and consequence analysis, the 95th percentile deposition velocity determined from the GENII2 output is recommended as input to either the MACCS2 or HotSpot software. Alternatively, the default value of 0.1 cm/s for an unfiltered release may be used.
Resuspension	Option available to user	Option available to user	Option available to user	Resuspension does not need to be modeled per DOE-STD-3009- given that this mechanism develops slowly; including this dose pathway is conservative.
Radioactive Decay During Plume Transport	Option available to user	Option not available to user	Option available to user	Decay of radioactive isotopes in the plume is a function of the travel time and the half-life of each specific radionuclide that is present in the plume. In practice, this effect is appreciable with radioisotopes of half-life on the same order or shorter than the time to reach the receptor under consideration. For non-reactor facilities, inadvertent criticality would be the primary accident type for which this factor is important.

6.1.9.1 MACCS2

The MELCOR Accident Consequence Code System (MACCS) code, and its successor, MACCS2, are based on a straight-line Gaussian plume model. MACCS (Chanin et. al., 1990, 1992a, 1992b) was developed originally for the Nuclear Regulatory Commission (NRC) whereas MACCS2 (Chanin and Young, 1995), an enhanced version, was developed with DOE applications in mind.

MACCS2 version 1.13.1 is a DOE toolbox code, and because it is a comprehensive and flexible code it is one of the most widely used codes in the DOE/NNSA complex. The MACCS2 package includes three primary enhancements: (1) a more flexible emergency response model; (2) an expanded library of radionuclides; and, (3) a semi-dynamic food-chain uptake model. The new code features allow detailed evaluations of potential consequences to workers at nearby facilities on large DOE reservations and allow the user to assess the potential impacts of over 800 radionuclides that cannot be considered with the earlier MACCS code.

MACCS2 requires significant user experience to set up input files which include:

- Range intervals;
- Population distribution;
- Weather scenario [constant weather, various variable-weather scenarios (such as using one year of hourly averages of wind speed and direction, stability class, precipitation), and type of weather sampling];
- Release height, number, and duration of plumes;
- Radionuclides released (over 800 can be specified in MACCS2, an increase of over 500 from MACCS);
- Organ doses and health risks;
- Dose conversion factors;
- Evacuation timing and routes;
- Costs of decontamination and interdiction;
- Sensible heat;
- Radiation shielding parameters; and,
- Deposition and resuspension.

WinMACCS version 3.10, a new version of MACCS2 with a Windows-based user interface, has been released, but has not yet been approved as a toolbox code (McFadden, et al., 2007).

MACCS2 has also been successfully used in modeling the atmospheric dispersion and consequences of a plume of Pu-239 particulates resulting from a High Explosive (HE) detonation, although it was not originally designed for that purpose.

The toolbox version of the code (MACCS2 V1.13.1) is not strictly compliant with DOE-STD-3009-94 Chg. Notice 3 Appendix A calculation requirements for determination of the overall site 95th percentile χ/Q. However, its results can be viewed as providing a reasonable approximation to this level of consequence, and can be used for the Option 2 χ/Q method from DOE-STD-3009-2014 Section 3.2.4.2. Historically, MACCS2 has been used to calculate the offsite 95th percentile χ/Q for DOE facilities despite the fact that the methodology used does not take into account variations in site boundary distances. As stated in DOE-EH-4.2.1.4-MACCS2-Code Guidance, *CFAST Computer Code Application Guidance for Documented Safety Analysis*:

"MACCS2 and MACCS do not comply fully with … (NRC Regulatory Guide 1.145 Position 3) methodology for determination of direction-independent 95th percentile dose to the offsite individual. It may be used to conservatively evaluate the 95th percentile direction-independent dose to receptors equidistant to the source.

Given site-specific data, the 95th percentile consequence is determined from the distribution of meteorologically-based doses calculated for a postulated release to downwind receptors at the site boundary that would result in a dose that is exceeded 5% of the time. DOE-STD-3009 allows for variations in distance to the site boundary as a function of distance to be taken into consideration. Assuming the minimum distance to the site boundary applies in all directions is a conservative implementation that is easily supported by MACCS2 and that essentially makes the calculations sector independent."

6.1.9.2 GENII

The Hanford Environmental Radiation Dosimetry Software System, GENeration II (GENII), is also based on a straight-line Gaussian plume model. GENII version 1.485 (Napier et. al., 1988), which is a DOS-based toolbox code, is available from RSICC as package CCC-601. A newer, Windows-based version, GENII version 2.10.1, with a user-friendly interface (FRAMES) has been evaluated and approved as a toolbox code.

The GENII code has been thoroughly documented and was developed under a stringent quality assurance program based on ANSI/ASME standard NQA-1. It has been used in consequence calculations by safety analysts for many years.

The GENII code is a comprehensive and flexible code with a strong emphasis on environmental dispersion processes beyond those of atmospheric dispersion (aquatic dilution, groundwater transport). (See Appendix F.) To quote from the APAC Working Group 5 report (APAC-5, 1998):

> *"GENII is a radiological assessment computer code system that estimates individual and collective doses to humans from the environmental transport of radionuclides in the atmospheric, surface water, and other environmental media, such as biotic transport and manual redistribution to the surface from buried waste. GENII is used for a variety of radiological assessments including 1) acute atmospheric releases, 2) chronic atmospheric releases, and 3) residual soil contamination."*

GENII 2.10.1 has extensive libraries of isotopes and associated dose conversion factors. It calculates doses from inhalation, ingestion, and external radiation (cloudshine and groundshine).

The required meteorological data to drive the code consists of JFDs of wind speed and stability class for each of the 16 wind directions, usually taken to be 22.5-degree azimuth compass directions, with the first one centered on north, etc. The toolbox version of the code (GENII version 1.485) is not strictly compliant with DOE-STD-3009-94 Appendix A calculation requirements for determination of the overall site 95th percentile dose. However, its results can be viewed as providing a reasonable approximation to this level of consequence. Users should also recognize that the older version uses atmospheric dispersion models that do not account for plume depletion from wet and dry deposition phenomena.

The GENII code also allows the user to specify radionuclide concentrations in the environmental media, as may be produced from another code or previous analysis. In this mode, GENII will calculate the corresponding radiological doses from various pathways.

6.1.9.3 HOTSPOT

The HotSpot Health Physics Codes, or HotSpot program, provides a first-order approximation of the radiation effects associated with the atmospheric release of radioactive materials. The toolbox version of this code is V2.07.1 (Homann, 2010) and, as with the other two radiological consequence codes, is based on the Gaussian plume model. The user inputs a 95 percent meteorological condition[31] and selects various source term options and dose output options. The software is also used for safety analysis of facilities handling radioactive material. HotSpot atmospheric dispersion model codes are a first-order approximation of the radiation effects associated with the short-term (less than a few hours) atmospheric release of radioactive materials.

HotSpot uses the radiation dosimetry methodologies recommended by the International Council for Radiation Protection (ICRP). These methodologies are summarized in three Federal Guidance Reports (FGRs) (FGR-11, FGR-12, and FGR-13). FGR-11 provides dose coefficients in the form of 50-year integrated dose equivalents for acute inhalation of radionuclides and is based on the biokinetic and dosimetric models of ICRP Publications 26/30. FGR-12 provides dose coefficients in the form of dose per unit time-integrated exposure for external exposure to radionuclides in air, water, or soil. FGR-13 provides dose coefficients using the new lung model from *Human Respiratory Tract Model for Radiological Protection* (ICRP-66, 1994) lung model and ICRP series 60/70 methodologies.

As is true for MACCS2, HOTSPOT is not strictly compliant with DOE STD-3009, and for the same reasons. A new version of HotSpot, version 3.0.1, has been released, but has not yet been approved as a toolbox code.

6.1.10 DOE-STD-3009-2014 ATMOSPHERIC DISPERSION OPTIONS

Three options are given in DOE-STD-3009-2014 to evaluate atmospheric dispersion and the resulting χ/Q:

- Option 1: Follow a process based on Nuclear Regulatory Commission (NRC) Regulatory Guide 1.145, *Atmospheric Dispersion Models for Potential Accident Consequence Assessments at Nuclear Power Plants;*
- Option 2: Use a DOE-approved toolbox code and apply the conservative parameters; or
- Option 3: Use site-specific methods and parameters as defined in a site/facility specific DOE-approved modeling protocol.

All three options evaluate the χ/Q at the MOI using either a 95th percentile for a "directionally independent" method or a 99.5th percentile for a "directionally dependent" method. NRC Reg. Guide 1.145 defines how to derive the "95th percentile directionally independent" and the "99.5th percentile directionally dependent" χ/Q values. For each of these, the minimum distances to the site boundary in 45°-wide sectors centered on 16 directions (N, NNE, NE, etc.) is to be derived and the χ/Q value for each hour during the year is to be calculated. The term "directionally independent" as used in DOE STD-3009-2014 means that the determination of the overall site 95th percentile χ/Q is calculated by creating a

[31] Hotspot V 2.07.1 and V 3.01 can also work with every hour observation.

cumulative probability distribution for all sectors combined based on all the meteorological annual data and using the actual site boundary distance for each sector and choosing the 95th percentile value. The "99.5th percentile directionally dependent" value is found by creating a cumulative probability distribution for each sector, determining the 99.5th percentile value for each, and choosing the maximum value.

The value of χ/Q using Option 1 can be accomplished manually using a spreadsheet. Option 3 allows the use of software generated at the site if it follows a site-approved modeling protocol. For Option 2, one of the toolbox codes is to be used. It should be noted that the oft-used MACCS2 software does not fully comply with NRC RG 1.145, as explained above, yet is accepted by DOE as the 95th percentile value for the closest point on the site boundary is conservative. POSTMAX V2.0 (Sartor, 2009), software developed at LANL, can be used to generate the 95th percentile value of χ/Q from the MACCS2 output that is compliant with NRC RG 1.145. POSTMAX2 has been subjected to software quality assurance (SQA) at LANL (Letellier and Ashbaugh, 2001) but it is not one of the toolbox codes, so therefore anyone using POSTMAX2 for a DSA will need to do their own SQA.

6.1.11 DISPERSION MODELING PROTOCOL

The following 15-step modeling protocol provides additional dispersion analysis guidance beyond that of Section A.7 of DOE-STD-3009-2014 and is applicable to both radiological and toxic chemical releases. This modeling protocol guidance addresses evaluation of the MOI receptor, as appropriate, for submittal to the DOE Safety Basis Approval Authority (SBAA) for approval prior to its application. Guidance for implementing the recommendations below can be found elsewhere in this chapter, Chapter 7, and in related appendices. The 50-mile population dose calculation is included for situations where accidents cannot be prevented or mitigated to less than the 25-rem Evaluation Guideline (EG) and a comparison to DOE P 420.1, *Department of Energy Nuclear Safety Policy*, may be required; or if necessary, for evaluation of beyond DBA/EBA accidents to provide a risk perspective of any "cliff edge" effects or insights for emergency planning. The 100 m co-located worker receptor is not included in this modeling protocol since guidance has already been established in OE-3.Key assumptions and inputs that are different than the MOI dispersion analysis are documented in the DSA Chapter 3 hazard evaluation methodology, or alternately, in the accident analysis methodology.

1. Identify dispersion model and version number chosen and the basis for its selection:
    a. Identify dispersion model and version number chosen, and indicate whether it is an approved version of a toolbox code available through the DOE Central Registry.
    b. Describe the appropriateness of the modeling technique relative to the site-specific and facility-specific application and the basis for its selection.
    c. State whether the default values recommended in the DOE guidance document for the DOE Central Registry toolbox code will be used, or technically justify the use of alternate values.
    d. If a DOE CR toolbox code is not used, describe the SQA assessment has been performed, or will be performed on the selected code.

    Note 1: Safety SQA requirements in DOE O 414.1D need to be met prior to using any code that is not in the DOE CR toolbox.

    e. In lieu of selecting a DOE CR toolbox code or other industry-accepted code, the proposed dispersion analysis may be performed within a spreadsheet, if it is documented as an engineering calculation that complies with DOE O 414.1Drequirements and any applicable site SQA requirements.

Note 2: DOE sites may choose any modeling approach it deems applicable to facility-specific phenomenology and site-specific atmospheric dispersion, as long as it is approved by the DOE SBAA prior to its application for the DSA accident analysis.

2. Specify the receptors to be evaluated:
   a. MOI
   b. Other sensitive receptors
   c. 50-mile population

3. Describe site- and facility-specific elements:
   a. *Release height*: Indicate the height of the release above plant grade and determine whether it is sufficiently high to escape the aerodynamic effect of nearby building(s) to become elevated.

      Note 3: If the release height is less than 2.5 times higher than nearby adjacent building(s), the release height should be set to zero (i.e., ground-level release).

      Note 4: If release is from a stack 2.5 times higher than nearby adjacent building(s), but the stack is not seismically-qualified, it should be treated as a ground-level release.

   b. *Terrain profile to determine potential interactions (plume impaction)*: If the release height is determined to be ground-level then terrain effects do not affect the analysis unless it is a dense gas release that may be gravity-fed into a nearby depression. For elevated releases, impaction of the plume on a downwind hill or mountain should be incorporated into the analysis. If a non-toolbox code has been selected to model the impact of terrain effects on atmospheric dispersion, describe the site's unique terrain profile.

   c. *Surface roughness data source (population, terrain, etc.)*: Identify the surface roughness or roughness type (i.e., urban, rural) applicable to the analysis for the site morphology and indicate how this affects the horizontal and vertical turbulence coefficients. Provide a technical basis for the establishment of site roughness parameters inclusive of tree types, density, configuration, topography, building locations and types, and local land use.

      Note 5: Surface roughness considers both upwind (i.e., fetch) and downwind characteristics of the release point, and the value used for the MOI could be different from that for a 50-mile population dose calculation.

   d. *Population distribution within 50-mile radius*: For population dose calculations, determine the population in each of the annular sectors, the census year represented, and whether day-night population distributions are to be applied and the justification their application.

      Note 6: Population doses are included in this Handbook since it may be of interest for special risk assessments to compare to the DOE Safety Goal in DOE P 420.1, Department of Energy Nuclear Safety Policy, and could be used to provide perspective should a facility have mitigated doses to the MOI that exceed the 25 rem EG.

   e. *Site map with locations of receptors of interest*: Develop a map of the DOE site with DOE-controlled property line and MOI site distances for the 16 sectors, in conformance with NRC Regulatory Guide (RG) 1.145, and other relevant boundaries, inclusive of the Perimeter Intrusion and Detection Alarm System or other security physical control boundaries.

f. *Location of release point(s)*: Develop a map that shows the location of all release points that are being analyzed, or describe whether the release is not associated with fixed locations (e.g., a release in a large outdoor waste staging area).

4. Describe release characteristics:

   a. *Initial plume dimensions*: Should the release become entrained in the wake and cavity of a nearby building, describe the method to calculate the initial horizontal and vertical plume dimensions, if treated as a virtual point source.

   b. *Positive and negative buoyancy*: If plume buoyancy occurs due to sensible heat of the release, or its density, as in a hydrogen release, indicate its applicability to the analysis and the analytical technique to be employed to account for it. For heavy gas (dense gas) releases, determine if the release quantity, temperature (i.e., cryogenicity), and/or density of the release, represented by the Bulk Richardson Number, would subject it to dense gas dispersion conditions and describe the analytical technique to be employed to account for it.

   c. *Elevated or ground-level release*: Based on the presence of a nearby or adjacent building, determine whether the release is elevated or down-washed to ground level. For elevated releases of gamma-emitting radionuclides, additional cloud shine dose calculations using an appropriate finite plume model may be necessary. Describe the finite plume model to be used.

   d. *Aerodynamic influence of nearby buildings*: Establish the appropriate code to account for the aerodynamic effect of the buildings on the release.

   e. *Energetic releases*: Identify the code to be used for each energetic release situation and the justification for its use. Releases from fires can be modeled with MACCS2 and Hotspot. For other energetic releases (e.g., detonations, deflagrations, delayed ignition, BLEVEs), non-Gaussian dispersion codes need to be employed.

      Note 7: ALOHA Version 5.4.4 is a toolbox code that is designed to address detonations, delayed ignition, radiant heat from a fire, and a BLEVE.

5. Describe source term phenomenology and characterization, as applicable to any particular accident scenarios:

   a. *Particulate and Pressurized Liquid Releases: Five Factor Formula (MAR, DR, ARF, RF, LPF)*: Include a discussion whether the unmitigated and mitigated source terms, as determined by the DOE-HDBK-3010-94 methodology, warrant any special considerations for input to the dispersion analysis, or state why there are none.

      Describe if the source term has any special physical release properties that may influence dispersion or consequence estimates. Indicate whether it will be modeled other than as a point source, not already addressed in the considerations above, or whether it will be modeled considering momentum from the discharge velocity, or as a buoyant release due to elevated discharge temperature of the release, fire, or explosion.

      If credited in the mitigated analysis, identify LPF from building configurations and presence or absence of HEPA filters.

   b. *Particulate and Pressurized Liquid Releases: Particle-Size Distribution*: Since particle size distribution spectra are very important for establishing RF, ARF, and deposition velocity, establish the applicable particle size distribution from DOE-HDBK-3010-94, supplemented by representative studies and experiments. If the particle size distribution is unknown, assume a conservative distribution from available data to bound the calculation.

c. *Pressurized and non-Pressurized Gaseous Releases: Release Period and Release Rate*: Determine gaseous release as a function of time for pressurized gaseous releases.

If gaseous release is constant and continuous (i.e., applying 10-minute EPA recommendation from 40 CFR 68, *Chemical Accident Prevention Provisions*, worst case guidance for DSA unmitigated analysis), establish a constant release rate as input to a peer-reviewed Gaussian plume model.

If release is for a brief period (i.e., less than a minute), establish a release quantity as input to a peer-reviewed Gaussian puff model.

d. *Pressurized Liquid and Gaseous Releases: Density with respect to ambient atmosphere*: Select appropriate code to address whether positive buoyancy or negative buoyancy is applicable.

Note 8: HPAC SCIPUFF has been used to address positively buoyant gases (i.e., hydrogen) and ALOHA, DEGADIS, SLAB and HPAC have been used to address negatively-buoyant gases (i.e., chlorine).

e. *Gaseous Releases: Reactivity on release to the atmosphere*: Effects of atmospheric chemistry should to be considered on releases that may undergo chemical transformation during transport to the MOI and population (e.g., uranium hexafluoride and anhydrous ammonia).

f. *Gaseous Releases: Fire scenario chemical transformation*: Oxidation of radionuclides or toxic chemicals in fires result in new substances, depending on temperature and availability of oxygen. Peer-reviewed literature should be consulted in the determination of the new substances to be evaluated.

Note 9: Seek assistance from a process chemical engineer or chemist to determine the new substances and their quantities to be evaluated.

g. *Pressurized Gaseous Releases*: Identify the size of the orifice and whether choked flow is applicable. Due to the nature of this type of release, it is non-linear and the release rate decreases with time.

Note 10: Consult technical literature for release rate characterization and if flow is choked by speed of sound limitation.

h. *Pressurized Liquid and Non-Pressurized Liquid Releases*: Determine the evaporation rate of the puddle using appropriate mass balance methodology. Puddle depth of 1 cm should be assumed unless release is confined in an impoundment basin.

Note 11: ALOHA Version 5.4.4 has a useful mass-balance algorithm, or manual calculation methods presented in Appendix B can be applied.

i. *Pressurized Liquid Release*: Depending on the substance and the pressure and temperature that it is stored, the release will be in two phases. Immediate flashing results in a gaseous puff and a puddle. The puff should be evaluated with a Gaussian puff model and the subsequent puddle evaporation by a Gaussian plume model.

Note 12: HPAC and ALOHA Version 5.4.4 contain useful algorithms to determine flash-aerosol-puddle quantities. Manual calculation methods presented in Appendix C can also be applied.

j. *Sensible Heat from Fire*: Determine impacts of sensible heat from fire in terms of radiant heat impacts on human skin exposure and on facility integrity.

Note 13: ALOHA Version 5.4.4 contains useful algorithms to determine radiant heat impacts of sensible heat.

k. *Deflagration*: Determine energetic release propagation rate. If slower than the speed of sound, a deflagration fireball results. Select the appropriate peer-reviewed code to establish impacts to workers, public, the environment, and SSC integrity.

Note 14: NASA fireball code (Dobranich et. al., 1997) addresses this phenomenology and the analyst may wish to consult this report for guidance.

l. *Detonation*: Determine energetic release propagation rate. If faster than the speed of sound, a detonation occurs. Select the appropriate peer-reviewed code to establish impacts to workers, public, the environment, and SSC integrity.

Note 15: ALOHA Version 5.4.4 contains useful algorithms to determine overpressures from detonations.

m. *Detonation (delayed ignition)*: Delayed ignition detonations may occur hours after release and depend on the mechanical turbulence generated by obstacles (trees, buildings) in its transport path.

Note 16: ALOHA Version 5.4.4 contains useful algorithms to determine overpressures from delayed ignition detonations.

n. *BLEVE*: Determine whether a fire of a tanker or container can result in a BLEVE.

Note 17: ALOHA Version 5.4.4 contains useful algorithms to determine overpressures from a BLEVE.

6. Describe meteorological data sources and assure its fidelity:

a. *Onsite instrumented meteorological tower*: Indicate whether an onsite source of representative meteorological data is available and if so, indicate location(s) of meteorological tower(s) on site map with release locations. The meteorological program should monitor wind speed, wind direction, and an indicator of atmospheric stability (e.g., temperature difference, sigma theta, sigma phi).

b. *Height(s) of measurement*: Identify the heights of measurement for each of the meteorological parameters that will be used in the analysis. Ideally, wind speed and wind direction data are measured at the standard 10-meter height. If wind speed is measured at a non-standard height, wind speed power law height adjustments should be considered. The temperature difference minimum height should be at least 35 meters.

c. *Certification of data quality*: Indicate whether the onsite meteorological data has been quality assured under the guidance of Section 7.4 of ANSI/ANS-3.11-2005(R2010). Provide a certification from the site meteorological program manager, or other organization accountable for the effective operation of the meteorological program.

d. *Pre-processing and averaging methodology*: Demonstrate that the raw meteorological data have been appropriately pre-processed and averaged to be applicable to the assessment.

e. *Missing data handling techniques*: Since all meteorological data bases have some gaps due to calibrations and instrument malfunctions and missing data needs to be addressed, demonstrate that the data base has appropriate missing data handling as part of its quality assurance program.

f. *Offsite representative meteorological source (e.g., National Weather Service)*: If quality-assured onsite meteorological data are not available, determine a surrogate data source nearby the site and demonstrate that it is spatially representative.

7. Describe meteorological data application to dispersion assessment:

   a. *Applicable meteorological parameters*: State which meteorological parameters will be used in the dispersion assessment.

   b. *Calm wind speed threshold and handling methodology*: Calm wind speed handling methodology is very important to consequence assessments since very light wind speeds are part of the 95% and 99.5% meteorology. Demonstrate that calm wind speeds are appropriately handled in the data base and are tied to the threshold wind speed limitations of the mechanical or sonic anemometry.

   c. *Turbulence typing methodology*: Choose the technique to type turbulence (e.g., delta temperature, sigma theta, sigma phi, split-sigma, Richardson number, Monin-Obukhov similarity) and demonstrate that the methodology selected is representative of the site's roughness and other site-specific and facility-specific characteristics.

   d. *Incorporation of surface roughness in turbulence typing*: Since surface roughness affects mechanical turbulence generation, the horizontal and vertical dispersion coefficients should reflect this. Demonstrate whether the site should be characterized as a rural or urban site by profiling the site's roughness.

   e. *Wind speed power law height adjustments*: If wind speed and wind direction measurements are at any height except the standard of 10 meters, appropriate wind speed power law adjustments should be invoked. Power law exponents are a function of atmospheric stability class. Indicate which power law methodology is employed and why it is applicable to the site.

8. Select meteorological data period:

   a. *1-5 years*: At least 5 years of recent meteorological data are needed to demonstrate temporal representativeness. Identify the years of data that will be evaluated, and explain any anomalies, such as years being excluded if not able to be certified. If data base is shorter than 5 years, a representativeness demonstration is required to determine any uncertainties.

   b. *More than 5 years*: If meteorological data are available in this temporal range, use as much as are available. The larger the data base, the less likely a climatological "Black swan" is missed in the statistics.

9. Select appropriate atmospheric dispersion coefficients:

   Demonstrate that the dispersion coefficients are applicable to site characteristics. The dispersion coefficients can be taken from the following menu:

   a. Pasquill-Turner-Gifford (PTG, rural terrain)

   b. Briggs urban and rural

   c. McElroy-Pooler (urban terrain)

   d. Eimutis and Konicek curve fitting of the PTG data

   Note 18: Eimutis and Konicek are used in MACCS2. However, the analyst should be aware of the table lookup error in the toolbox version of the MACCS2 code.

e. Tadmor and Gur

Note 19: Tadmor and Gur are used in MACCS2, but are not recommended for MOIs within 500 m of the release.

f. Other dispersion coefficients resultin from special site atmospheric tracer studies and/or other peer-reviewed evaluations.

10. Select plume averaging time, if different from release duration, and demonstrate its applicability to selected horizontal and vertical dispersion coefficients.

    a. Choose from 3-, 10-, 30-, and 60-minute periods, or any other period, if justified. The 10-minute period is the standard period used in atmospheric dispersion and no applicability demonstration is required if it is selected.

11. Describe release duration and exposure period:

    a. Demonstrate that the selected release duration range is applicable to the assessment.

    b. Use peer-reviewed Gaussian plume code for releases longer than one minute or a peer-reviewed Gaussian puff code for a period shorter than one minute.

12. Describe aerodynamic building effects:

    a. *NRC RG 1.145 technique***:** Demonstrate that this conservative plume downwash into the lee-side cavity is applicable to the assessment.

    b. *Other peer-reviewed technique***:** Identify other peer-reviewed technique and demonstrate that this other technique is applicable to the assessment.

13. Describe dry deposition and plume depletion:

    a. *Dry deposition technique*: Indicate whether the dispersion assessment will include dry deposition and provide justification for the site-specific methodology employed.

    Note 20: For tritium dispersion modeling, an appropriate deposition velocity needs to be justified.

    b. *Plume depletion technique*: Indicate whether the dispersion assessment will include plume depletion and provide justification for the site-specific methodology employed.

14. Describe χ/Q statistics and determine applicability to the assessment.

    a. *Direction-Independent (overall site) 95-percentile*: Usual choice for conservative evaluations of the cumulative distribution of the annual meteorological data for all 16 sectors accounting for the distance to site boundary in each sector.

    b. *Direction-Dependent 99.5-percentile*: Acceptable alternative to the direction-independent 95th percentile for conservative evaluations based on the maximum sector cumulative distribution.

    c. *Other percentile*: Demonstrate applicability to the dispersion assessment of any other percentile than those above.

15. Provide a summary of the basis for the conclusion that the selection of the parameters and input values, as identified above, will provide an overall radiological dose or chemical exposure consequence that is bounding and conservative. Include a list of conservatisms below.

6.2 RADIOLOGICAL CONSEQUENCE ASSESSMENT

This section and Appendix G provide guidance to the safety analyst regarding evaluation of radiological doses and health risks. They discuss the different types of radiation and the effects these radiation types can have on the human body, its organs, and its tissues. The factors that are considered in estimating the dose a receptor may receive following the atmospheric release of radioactive material are covered in detail. Finally, the health risks associated with radiological doses and the standards for radiation protection, in terms of allowed dose or air concentration, are discussed.

6.2.1 RADIOLOGICAL DOSE FUNDAMENTALS

Radiological doses arise from exposure to plumes of radioactive material, including deposition from plumes, and from exposure to prompt (direct) radiation from a criticality. The general modes of exposure include:

- inhalation of radioactive material (particulates and gases) while immersed in a plume;
- inhalation of particulates from deposited material that have been resuspended by traffic and/or by wind;
- ingestion of food products through meat, vegetable and fish pathways and ingestion of water contaminated by deposition from the plume;
- gamma radiation from the plume (cloudshine);
- gamma radiation from particulates deposited on the ground from deposition (groundshine);
- skin contamination from deposition; and
- prompt (direct) radiation from a criticality.

As described in Section 3.2.4.2 of DOE-STD-3009-2014, radiological consequences for the DSA accident analysis are presented as a TED based on integrated committed dose to all target organs, accounting for direct exposures as well as a 50-yr commitment. The dose pathways to be considered are inhalation, direct shine, and ground shine. Direct shine and ground shine from gamma emitters only need to be evaluated if they cause an upward change in the consequence level as defined in Chapter 2. Slowly-developing dose pathways, such as ingestion of contaminated food, water supply contamination, or particle resuspension, are not included. However, quick-release accidents involving other pathways, such as a major tank rupture that could release large amounts of radioactive liquids to water pathways, should be considered. In this case, potential uptake locations should be the evaluation points for radiological dose consequences.

Of principal concern for most DOE sites are criticalities and exposure to actinide particulates. DOE-STD-3009-2014 specifies that ingestion, resuspension, and skin contamination need not be included in a DSA. In the case of a criticality, doses arise from both the plume of fission products that may be released and from the prompt radiation. Prompt radiation from a criticality is of concern only for workers located near the accident site since effects from criticality accidents are generally confined to the near-field. The distance of concern for prompt radiation depends upon the size of the criticality (number of fissions) and the amount and type of shielding (such as concrete walls) between the worker and the site of the criticality. On the other hand, for actinide exposure, inhalation of Pu-239 particulates is the primary radiological concern as the body does not have any excretory mechanisms to remove it. For actinide releases, cloudshine, groundshine, skin contamination, and ingestion doses are insignificant in comparison (NUREG-1140), with the exception of the release of significant gamma emitters where cloudshine doses would become meaningful. Radiological dose from inhalation of enriched uranium particulates is of lesser concern and inhalation of depleted uranium particulates is trivial by comparison.

For uranium, chemical toxicity is normally of greater concern than its radioactivity.

6.2.1.1 TYPES OF RADIATION

Four types of radiation are important in DSAs: alpha (α), beta (β), gamma (γ), and neutron. The α, β, and γ radiations are emitted from atomic nuclei during radioactive disintegration, or decay, of the nucleus. Alpha particles are energetic helium nuclei; consisting of two protons and two neutrons, with a charge of +2[32]. Beta particles are energetic electrons, with a charge of -1, or positrons, with a charge of +1; they have a mass about 0.01 percent that of the alpha particle. Gamma radiation consists of electromagnetic waves, or photons, and have energy similar to that of x-rays. Being photons, gamma rays have neither charge nor mass. Gamma radiation typically accompanies alpha and beta radiation when an atomic nucleus disintegrates. Neutron radiation is emitted when a nucleus fissions, or breaks into fragments, such as during a criticality[33]. Neutron radiation consists of energetic neutrons, particles with zero charge and mass similar to that of protons, that is, about 25 percent of the mass of alpha particles.

When any or all of these radiations strike an organ or tissue of the body, they can deposit some or all of their energy, causing cell damage. The manner of energy deposition varies with the type of radiation. Some types of radiation, principally alpha and beta, deposit their energy primarily through the production of ionization. When they strike an atom, they strip off an electron, thus ionizing the atom. The two charged particles formed, the electron and the ion, are referred to as an ion-pair. The electron that is stripped off the atom may be sufficiently energetic that it can cause further ionization. The amount of ionization created depends upon the mass, charge, and energy of the particle. Particulate radiation (α, β, and neutron) can also deposit its energy through the dissociation of molecules and through elastic scattering, which causes heating.

Alpha-decay energy is typically on the order of several million-electron volts (MeV)[34]. For example, plutonium, uranium, and americium isotopes all emit alpha particles with energies on the order of 5 MeV. Because an alpha particle is doubly charged and massive, it can ionize many atoms before exhaustion. For example, an alpha particle traveling through air will create on the order of 50,000 ion pairs for each centimeter it travels. Because it creates so much ionization, it deposits its energy quickly, and penetrates only a short distance into a tissue.

Beta-decay energy is typically on the order of tens of keV to a few MeV. For example, the beta-decay energy of Pu-241 is 21 keV. During beta decay, the emitted electron, or positron, is accompanied by a neutrino or anti-neutrino, with which it shares the energy. The beta-decay energy is the sum of the energies of the electron and neutrino. Thus, for Pu-241, the maximum energy the electron can have is 21 keV; normally, it will have only a fraction of this. Because the beta particle is singly charged and not very massive, it cannot create nearly as much ionization as an alpha particle. A beta particle traveling through air will create on the order of 100 ion pairs for each centimeter it travels. In addition to causing ionization, beta particles also can be scattered elastically by atomic electrons. Because a beta particle does not lose its energy as rapidly as does an alpha particle, and because of elastic scattering, it can penetrate more deeply into tissue. However, it travels an irregular path in tissue because of elastic

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[32] The basic unit of charge is that of the electron, but with a reversal of sign. The charge of an electron is -1.60E-19 coulomb.

[33] Neutrons can also be produced through (α,n) reactions, in which an alpha particle strikes the nucleus of an atom, causing the emission of a neutron. This is generally not important for dose calculations as the additional dose from the neutron radiation is balanced by the decreased dose from the lost alpha particle.

[34] An electron volt (eV) is the kinetic energy of an electron after being accelerated through an electric potential difference of 1 V. It is equal to 1.60E-19 J.

scattering. This gives rise to the emission of electromagnetic radiation called *bremsstrahlung* (German for "braking radiation"), which in turn can deposit its energy in the surrounding tissue.

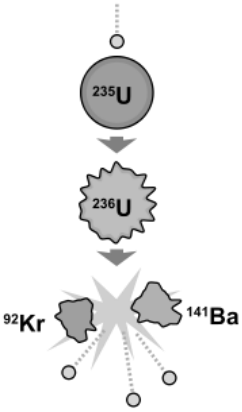
The energy of a gamma ray is typically on the order of tens of keV to a few MeV. For example, the energy of one of the several possible gamma rays that accompanies the alpha decay of Pu-239 is 52 keV. A gamma photon will typically create only about one ion-pair per centimeter in air. A gamma photon can also lose its energy through Compton scattering from electrons and even from interactions with the nucleus of an atom; although the latter are minor in comparison with photoionization and Compton scattering. Gamma radiation is capable of penetrating deeply into a person's body.

The energy of a fission neutron is typically on the order of a few keV to about 10 MeV. Because the neutron has no charge, it will not create many ion-pairs. It loses it energy primarily through elastic scattering. However, it can also cause nuclear transformations, especially when it has slowed, through elastic scattering, and become a "thermal" neutron. These nuclear transformations can lead to the emission of other radiations, such as α and γ. Neutron absorption through nuclear transformation is primarily by hydrogen and nitrogen in the human body. Elastic scattering of neutrons is primarily by the hydrogen in the body. Like gamma radiation, neutron radiation is very penetrating.

6.2.1.2 NUCLEAR FISSION

Nuclear fission typically yields two large fission fragments (nuclei of other isotopes), multiple neutrons, and other radiation (alpha particles, beta particles, or gamma rays). Fission fragments are typically highly radioactive. To reach a stable configuration, these fission products may continue emitting radiation for wide-ranging time periods; from milliseconds to many years.

Neutrons resulting from fission are categorized as either prompt or delayed. Prompt neutrons are emitted virtually simultaneously with fission (< 1E-14 second); whereas delayed neutrons may not be emitted for many seconds after fission. Prompt neutrons are "born" fast and are of high energy in the 1-20 MeV range, while delayed neutrons are relatively slow and of lower energy in the < 1 MeV range.



As an example, in the sketch to the right, a ^{235}U nucleus absorbs a neutron, becomes unstable, and fissions into two radioactive isotopes; ^{92}Kr and ^{141}Ba, while also releasing three neutrons and multiple gamma rays (not shown).

6.2.1.3 RADIOACTIVE DECAY AND HALF-LIVES

Radioactive decay is the spontaneous disintegration of a radioisotope accompanied by emission of ionizing radiation (α, β, and/or γ). It is the process by which a nucleus of an unstable atom reaches a more stable configuration by the release of energy or mass. The activity of a radioisotope is measured in units of rate of decay, commonly called disintegrations per second (dps)[35]. Lower radioisotope activities are typically measured in disintegrations per minute (dpm).

Specific activity is the activity per unit mass, and is measured in units such as Bq/kg or Ci/g. The specific activity of Ra-226 was originally defined as 1 Ci/g. The specific activity of a mixture of radionuclides is

[35] The SI unit is the Becquerel (Bq), defined as one dps. The historical, and still commonly used, unit of activity is the curie (Ci), which is equal to 3.7E+10 dps. Thus, 1 Ci = 3.7E+10 Bq.

the sum, over all the radionuclides in the mixture, of the products of specific activities and mass fractions.

The activity of a sample of any given radionuclide decreases exponentially with time, providing it is not being created by the decay of another radionuclide. If N is the number of atoms of a specific type of radionuclide in a sample of material, the change in this number, dN, in a small interval of time, dt, is proportional to N and to dt. This is written

$$dN = -\lambda N\, dt \qquad \textbf{Equation 6.2-1}$$

where the negative sign is needed to show that N decreases with increasing time. The constant of proportionality, λ, is called the decay (or transformation) constant and is measured in inverse time units, such as s^{-1}. The disintegration rate, or activity (A), is given by

$$A = -dN/dt = \lambda N \qquad \textbf{Equation 6.2-2}$$

The solution to equation (6.2-1) is

$$N = N_0\, e^{-\lambda t} \qquad \textbf{Equation 6.2-3}$$

where N_0 is the number of atoms at time t = 0. Thus, equation (6.2-2) can be written

$$A = A_0\, e^{-\lambda t} \qquad \textbf{Equation 6.2-4}$$

where $A_0 = \lambda N_0$ is the activity at time $t = 0$.

Because the decay is exponential, the time interval to decrease the number of atoms in a sample by a given factor is a constant. For example, the time to decrease by a factor of two, called the half-life ($t_{½}$), is obtained by inverting equation (6.2-3):

$$t_{½} = -(1/\lambda)\, \ln(½\, N_0/N_0) = (1/\lambda)\, \ln(2) = 0.693/\lambda. \qquad \textbf{Equation 6.2-5}$$

The half-life of Pu-239, for example, is 2.44E+04 yr, while that of U-235 is 7.1E+08 yr. The specific activity of U-235 is therefore about 30,000 times smaller than that of Pu-239, which is the main reason it does not present as great a radiological hazard as Pu-239 for a given amount of material as it is producing fewer decays, and therefore less energy, per unit time.

Instruments that measure the amount of radioactivity in a material usually present their results in terms of counts per minute (cpm). These are then converted to disintegrations per minutes (dpm) by knowing the efficiency of the counter and geometry of the measurement. In the case of surface contamination, the measurements are typically expressed in terms of activity per unit of area, such as cpm/100 cm^2, which are then converted to dpm/100 cm^2. To derive the amount of material involved, the dpm is divided by 60 to get dps, or Bq. This activity can then be converted to the number of atoms of the radionuclide present by dividing by the decay constant, or the number of grams present by dividing by the specific activity.

6.2.2 EFFECTS OF RADIATION ON THE BODY

Radiation damages the body as it deposits its energy, primarily through ionization, in organs and tissues. Because alpha radiation can be stopped by the body's outermost layer of dead skin cells, it poses no external hazard to the body; rather, its hazard is through inhalation. Beta radiation can barely penetrate

the skin to cause some damage; and it can also damage the eye. Like alpha radiation, its damage comes principally from inhalation and it also comes from ingestion. Gamma radiation and neutrons, on the other hand, can penetrate the body directly from external sources; material that emits gamma radiation and neutrons can, of course, be inhaled or ingested, but this is not the normal mode of exposure. Skin contamination from fallout from the plume causes tissue damage principally from β radiation.

Both short-term (acute) and long-term (chronic) exposures are important. External radiation from cloudshine, groundshine, skin contamination, or prompt radiation typically gives a short-term or even instantaneous dose, whereas internal radiation from inhalation and ingestion gives a long-term committed dose. A long-term dose can also arise from continual exposure to external radiation, as in a work place. If a radioactive particle is inhaled or ingested, it will cause damage as long as it remains in the body, because it contains many radioactive atoms that continue to disintegrate. An organ or tissue irradiated for an extended time (chronic exposure) may develop cancer or suffer other deleterious effects.

6.2.2.1 DOSE EVALUATIONS

Dose is expressed as an absorbed dose, that is, the amount of energy deposited in matter, or as an equivalent dose, a measure of damage done in tissue. The traditional unit of absorbed dose is the rad (radiation absorbed dose) and is defined as 100 ergs absorbed in 1 g of material. The newer standard international unit is the gray (Gy), which is defined as 1 J absorbed in 1 kg of material. Thus, 1 Gy = 100 rad. This equality applies to any type of radiation absorbed in any type of material.

The dose of most interest in accident analysis is the equivalent dose, as this is a measure of the biological damage. The amount of damage depends upon the type of radiation as well as the amount of energy absorbed. The equivalent dose H_T to a particular tissue T is equal to the absorbed dose D_T in that tissue times a radiation-weighting factor w_R

$$H_T = w_R D_T \qquad \textbf{Equation 6.2-6}$$

where w_R is a measure of the amount of damage done by the radiation. If more than one type of radiation impacts the tissue, H_T is calculated by summing over all radiation types. Appendix G gives the radiation weight factors (ICRP-60, 1991) for the four radiation types considered here.

The traditional unit for equivalent dose is the rem (roentgen-equivalent, man). The newer international unit is the sievert (Sv). The relation between them is the same as between gray and rad (1 Sv = 100 rem).

Example: Assume a medical x ray gives the lungs an absorbed dose of 20 rad (0.2 Gy). The equivalent dose would be 20 rem (0.2 Sv), as x-rays are similar to gamma rays and have a radiation weighting factor of one. On the other hand, if the absorbed dose of 20 rad to the lungs were from inhalation of plutonium, an alpha emitter, the equivalent dose would be 400 rem (4 Sv), as the radiation-weighting factor for alpha radiation is 20.

6.2.2.2 TYPES OF DOSE

Doses arise from both internal and external exposures, as noted above. Per DOE-STD-3009-2014, the only internal exposures of concern consist of inhalation from the plume. The external exposures are from cloudshine, groundshine, and prompt (direct) radiation from a criticality. These are discussed individually below.

6.2.2.2.1 INHALATION (PLUME)

Inhalation dose from a plume to a given organ or tissue from a given isotope, *i*, is the product of the amount of respirable radioactive material released, or the source term *ST*, atmospheric dispersion factor χ/Q, breathing rate *BR*, and dose conversion factor DCF_i

$$\text{Dose}_i = ST_i \times \chi/Q \times BR \times DCF_i \qquad \textbf{Equation 6.2-7}$$

assuming the receptor remains exposed for the duration of the plume. The total dose to the organ or tissue is the sum over all isotopes inhaled. The source term (ST_i) is the product of the material at risk (*MAR*), damage ratio (*DR*), airborne release fraction (*ARF*), respirable fraction (*RF*), and leakpath factor (*LPF*), as discussed in Chapter 5. The dose conversion factors are discussed below. The breathing rates for the "reference man" for various activities, as have been used in accident analyses for the past several years at many DOE sites, are given in Table 6-6 (ICRP-2, 1977 and ICRP-30, 1979–1982). ICRP-66 (1994) gives revised breathing for the "reference man"[36]. These are also shown in Table 6-6. Still other breathing rates are appropriate for other individuals, such as infants, the elderly, and the infirm, and for other levels of activity (ICRP-66, 1994). The analyst needs to choose which breathing rate is appropriate for the scenario being evaluated, taking into account the possible need to be consistent with earlier analyses.

DOE-STD-3009-2014 Section 3.2.4.2 requires a breathing rate of 3.3E-4 m^3/s. This value was initially developed for "light activity" based on data and methods from ICRP-2 / ICRP-30 DCFs, and is equivalent to "light work" as defined in ICRP Publication 68 using ICRP Publication 66 data. ICRP 68 has revised the 8-hour day breathing rates as follows: light work is defined as 2.5 hr sitting (inhalation rate 0.54 m^3/hr [1.5E-4 m^3/s], breathing frequency 12/min) and 5.5 hr light exercise (inhalation rate 1.5 m^3/hr [4.17E-4 m^3/s], breathing frequency 20/min). NNSA SD G 1027, *Hazard Categorization and Accident Analysis Techniques for Compliance with DOE Order 5480.23, Nuclear Safety Analysis Reports to Address Areas in Need of Clarification and Improvement* (Admin Change 1, May 2014) has added significant figures (to bring it to 3.3333E-04 m^3/s), although this added precision is unwarranted.

Table 6-6. "Reference Man" Breathing Rates for Various Levels of Activity.

Activity Level	Breathing Rate (m^3/s)
ICRP-2, ICPR-30	
Chronic	2.66×10^{-4}
Light	3.33×10^{-4}
Heavy	3.47×10^{-4}
ICRP-66	
Sleep	1.25×10^{-4}
Rest, sitting	1.50×10^{-4}
Light exercise	4.17×10^{-4}
Heavy exercise	8.33×10^{-4}

Once radioactive material enters the lungs, it begins to migrate to other parts of the body. A portion is transferred directly to the blood and another portion to the stomach. Transfer of the material directly from the lungs into the blood depends upon where in the lungs it is deposited and how soluble it is. Material is

[36] The reference man is a Caucasian male, 30 years old, height 176 cm (5 ft, 9 in.), and weight 73 kg (161 lb).

also cleared from the lungs by means of the body's mucociliary mechanism and then swallowed, thus entering the gastro-intestinal (GI) tract. The fraction f_1 of the material that passes from the GI tract into the blood, primarily from the small intestine, depends on the solubility of the material. For some radionuclides, such as iodine, the transfer to the blood is nearly complete ($f_1 = 1.0$). For others, such as plutonium, the portion transferred to the blood is much less than 1 percent; the remainder is excreted. Once the material enters the blood, it can be carried to any part of the body. From there, it may preferentially attach to a given organ or tissue, as determined by the chemical properties of the radioactive material and of the organ or tissue. For example, plutonium and americium become preferentially attached to bone surface. The amount of biological damage that radioactive material may inflict on an organ or tissue is given by the Dose Conversion Factor (DCF) mentioned above. For inhalation, this is typically expressed in units of Sv/Bq (or rem/Ci), which can be converted to Sv/g (or rem/g) by multiplying by the specific activity. Tables of DCFs for a large number of radionuclides are given in FGR-11 (EPA, 1989). The DCFs take into account the migration of the radioisotope within the body, the decay of the radioisotope, and the formation of daughter isotopes that may be radioactive.

The residence time of a radioactive particle in the lungs depends in part upon the solubility of the material. Three broad categories for use with ICRP-30/FGR-11 DCFs have been defined:

Y: Radionuclides in insoluble compounds typically remain in the lungs for a long time; these are of Solubility Class Y (for years), also called Lung Clearance Class Y.

W: Radionuclides in moderately soluble compounds remain in the lungs for weeks; these are of Solubility Class W (for weeks), also called Lung Clearance Class W.

D: Radionuclides in soluble compounds remain in the lungs for only a short time; these are of Solubility Class D (for days), also called Lung Clearance Class D.

According to FGR-11 (EPA, 1989), plutonium compounds can be Class Y (the oxides[37]) or Class W (all other Pu compounds); there are no Class D Pu compounds. Americium compounds are only Class W. Uranium compounds can be Class Y (UO_2 and U_3O_8), Class W (UO_3, UF_4, and UCl_4), or Class D (UF_6, UO_2F_2, and $UO_2(NO_3)_2$). Fission products are of all three lung clearance classes.

Should these compounds be involved in a fire, their chemical nature may change. For example, a plutonium salt, as in certain residues, which is Class W, may change to an oxide (Class Y) in a fire. High-fired plutonium oxide is an example of Class Y. However, conversion of a salt in a fire will probably not be complete. To be conservative, assume that the resultant chemical form is the one that gives the largest dose; in the case of plutonium salts, for example, Class W for plutonium salts.

Newer biokinetic models of the human respiratory system (ICRP-68, 1994) give DCFs for plutonium and americium that are notably smaller than those used in ICRP-30 (1979–1982). The following differences can be noted between these two databases:

1. The DCFs for fission products are similar between the two databases, but those of the actinides are much smaller in ICRP-68 than in ICRP-30.

2. The ICRP-68 values do not use the D, W, and Y solubility classes. Instead, they use "Fast," "Moderate," and "Slow," which are broadly equivalent to D, W, and Y.

[37] Plutonium hydroxides have subsequently been added to Class Y.

a. "Fast" refers to those compounds that dissolve quickly and are absorbed into the respiratory tissue where they are initially deposited, or directly into the blood, in minutes to hours. There is virtually no time for these compounds to be transported to other respiratory sites.

b. "Moderate" refers to those compounds that dissolve more slowly. Only a small portion (modeled as 10 percent) is absorbed directly into respiratory tissue at the initial deposit site, or directly into blood; the remainder is transformed (in a period of weeks) into a more soluble compound. While in this transformed state, it can be transported to other respiratory tissues. It eventually is dissolved into the blood and thus is available for transport to other parts of the body.

c. "Slow" refers to those compounds that are essentially insoluble. Almost none of this material is absorbed directly into the tissue at the initial deposit site, or directly into the blood. It is slowly transformed into a more soluble compound (on a time scale of years). While in this transformed state, it can be transported to other respiratory tissues. It eventually is dissolved into the blood and thus is available for transport to other parts of the body.

3. The DCFs of ICRP-68 are given for two particulate size distributions, centered at 1 µm and 5 µm. These sizes are referred to as AMAD, the median diameter of a lognormal size distribution. In contrast, the ICRP-30 values were only for one particulate size distribution, 1-µm AMAD.

Dose Coefficients for Intakes of Radionuclides by Workers (ICRP-68, 1994) recommends that the 5-µm AMAD DCFs be used unless the analyst can justify the use of the DCFs for the 1-µm AMAD. The 5-µm AMAD is considered (in ICRP-68) to be more representative of the workplace environment than the 1-µm default values adopted in ICRP-30. An exception would be for the case in which the particulates had passed through high-efficiency particulate air (HEPA) filtration, in which case the 1-µm AMAD would be more appropriate. DCFs generally are larger for smaller particle sizes. HEPA filters are least efficient at about 0.3-µm for which the DCF would be larger than for either 1-µm or 5-µm. On the other hand, very small particles tend to agglomerate and stick to surfaces. The DCF chosen for a given scenario needs to be technically justified if other that the value for 1-µm or 5-µm.

Also, note that the deposition velocity depends on particle size. For the 0.3-µm particle, the recommended deposition velocity is 0.01 cm/s (HSS Safety Bulletin, 2011).

6.2.2.2.2 CLOUDSHINE

The amount of gamma radiation (and beta, if appropriate) received by a receptor from a plume of radioactive material depends upon the location of the receptor relative to the plume. The greatest dose would be received by a receptor in the plume centerline, of course, and dose conversion factors have been developed for such a receptor. The assumptions made in deriving these DCFs are that (1) the plume is uniform and semi-infinite ("semi" because the plume extends upward from the ground, but not downward) and (2) the receptor is standing upright on the ground. The dose received from a given radionuclide is the product of the concentration of the radionuclide and the DCF, integrated over the duration of the plume. The doses from all the radionuclides are then be summed. The DCFs for cloudshine are given in Federal Guidance Report No. 12, *External Exposure to Radionuclides in air, Water, and Soil* (EPA, 1993). Information for ordering this report can be found at the EPA internet web site http://www.epa.gov/radiation/federal/index.html. Cloudshine DCFs are expressed in units of (Sv-m^3)/(Bq-s). FGR-11 also gives DCFs for cloudshine but these have been superseded by those of FGR-12.

The cloudshine doses calculated using the DCFs from FGR-12 are conservative because of the assumptions that the receptor is standing upright in a uniform, semi-infinite cloud. The plume, of course, is neither uniform nor semi-infinite, the receptor may not be at plume centerline (and the plume may even be elevated), the receptor may be sheltered, and the receptor may not be standing up. Each of these factors would tend to reduce the dose. Corrections for finite cloud size and distribution (Gaussian) and for receptor locations off-centerline are included in several computer models of atmospheric dispersion and consequence assessment. The safety analyst may also wish to consider additional dose reduction factors associated with sheltering.

6.2.2.2.3 GROUNDSHINE

The amount of gamma radiation received by a receptor from radioactive material deposited on the ground through deposition depends upon the location of receptor relative to the fallout. The greatest dose would be received by a receptor at the center of the deposition, and dose conversion factors have been developed for such a receptor. The assumptions made in deriving groundshine DCFs are: (1) the material is uniformly distributed on the surface or in the soil for an infinite distance in every horizontal direction; and, (2) the receptor is standing upright on the ground. The dose received from a given radionuclide is the product of the concentration of the radionuclide on, or in, the ground and the DCF, integrated over the duration of the exposure (how long the receptor is present to receive groundshine). The groundshine doses from all the radionuclides are then summed. The concentration to be used in the calculation is either an areal concentration (Bq/m^2), if the material is only on the surface, or a volume concentration (Bq/m^3), if mixed with the soil. Groundshine DCFs are expressed in units of either ($Sv\text{-}m^2$)/(Bq-s) for surface contamination, or ($Sv\text{-}m^3$)/(Bq-s) for soil contaminated down to a specified depth. The DCFs for groundshine are given in FGR-12 (EPA, 1993). The depths of soil contamination considered in these tables are for 1-cm, 5-cm, 15-cm, and an infinite depth. Groundshine DCFs for other depths of soil contamination can be found by interpolation among these tables.

The groundshine doses calculated using the DCFs from FGR-12 are conservative because of the assumptions that the receptor is standing upright on a uniformly contaminated, infinite plane. The deposition, of course, is neither uniform nor infinite and the receptor may not be the middle of it. Furthermore, surface irregularities (uneven terrain) tend to shield the receptor, the receptor may be sheltered, and the receptor may be elevated. Each of these factors would tend to reduce the dose. The safety analyst may also wish to consider additional dose reduction factors associated with sheltering or surface roughness / unevenness.

In calculating groundshine doses, the time variation of the ground concentration at the receptor's location is considered. In the early stages of plume passage, the ground concentration is increasing; the concentration reaching a peak at the end of plume passage. Resuspension of the particulates then erodes the amount of contamination. The DOE-STD-3009 recommended exposure duration is up to 8 hours.

6.2.2.2.4 PROMPT (DIRECT) DOSE

Doses from criticalities arise from both the plume of fission products that may be released and from prompt radiation, that is, the gamma rays and neutrons that are emitted during the brief (millisecond) energy burst(s) during the criticality spike(s). The prompt dose depends upon the number of fissions in the criticality, the distance to the receptor, and the amount of intervening shielding material, such as concrete. NUREG/CR-6504, *An Updated Nuclear Criticality Slide Rule, Functional Slide Rule,* gives curves of unshielded dose as a function of distance, number of fissions, and time after the criticality. The unshielded gamma and neutron doses can also be estimated from the following equations taken from the

(now withdrawn) NRC Regulatory Guides 3.33, 3.34, and 3.35, and then summed. The unshielded gamma dose is

$$D_\gamma = (2.1E\text{-}20)\ N\ d^{-2}\ e^{-3.4d}$$ **Equation 6.2-9**

and the unshielded neutron dose is

$$D_n = (7E\text{-}20)\ N\ d^{-2}\ e^{-5.2d}$$ **Equation 6.2-10**

where:

D_γ = gamma dose (rem),

D_n = neutron dose (rem),

N = number of fissions, and

d = distance from the source (km).

Shielding is expressed in terms of the amount of intervening concrete or the equivalent if other shielding materials are involved. Shielding dose reduction factors may be determined from the following relationships, which are taken from NUREG/CR-6504 (NRC, 1998):

Steel Dose Reduction Factor:	neutrons, = exp(-0.256 × steel thickness in inches) gammas, = exp(-0.386 × steel thickness in inches)
Concrete Dose Reduction Factor:	neutrons, = exp(-0.240 × concrete thickness in inches) gammas, = exp(-0.147 × concrete thickness in inches)
Water Dose Reduction Factor:	neutrons, = exp(-0.277 × water thickness in inches) gammas, = exp(-0.092 × water thickness in inches)

Prompt doses from criticalities need to be compared with the SS structure, system, and component guidelines for the facility worker (Chapter 2). These guidelines state that “prompt death” or “serious injury” is a high consequence. These refer to deterministic health effects, not cancer. A prompt dose from a criticality of 450-rad is considered lethal to 50% of the people within 30 days, a dose typically labeled $LD_{50/30}$. A dose of about half of this would cause serious injury but not death to most individuals. It is recommended that if the prompt dose exceeds 400 rad it be considered lethal (prompt fatality or “high consequence”). A prompt dose between 200 and 400 rad would cause serious injury (also a “high consequence”) and a prompt dose below 200 rad would not be a serious injury for a healthy worker. For a criticality involving 1E+17 fissions, a dose of 400 rad would be received by an unshielded worker within about three meters of the accident. Because the Facility Worker could be within this distance, criticality accidents involving 1E+17 fissions or more are considered “high consequence”. However, criticality accidents involving fewer fissions need to be evaluated on a case-by-case basis.

Prompt doses from a criticality may also need to be included in the assessment of consequences to the co-located worker located a minimum of 100 m if it is significant compared to the plume inhalation and cloudshine dose. The unmitigated analysis may credit shielding from passive design features such as concrete walls, and their safety significance evaluated per the DOE-STD-3009-2014 guidance on initial conditions.

6.2.2.3 PLUTONIUM EQUIVALENT CURIES

Sometimes for simplification of accident analysis calculations it is beneficial to introduce the concept of surrogate compositions of MAR, based on isotopic-specific DCFs. For example, the concept can be used to establish a common inventory or tracking basis for a dose calculation. It can provide a process for accepting new material while remaining within the bounds of the accident analyses, thus allowing operational flexibility while complying with the safety basis and source strength administrative control limits.

This is commonly done in the case of materials composed of several isotopes of plutonium. For accident analysis purposes and safety system classifications evaluation guidelines are in units of TED, which is indifferent to the dose pathway or the kinds of radionuclides are involved. The dose equivalent curie concept effectively converts radiological consequences for individual isotopes or mixes of isotopes to the same consequences from a corresponding amount of a base isotope. For example, for Pu-239, a plutonium equivalent curie (PE-Ci) is defined as the summation of the curies of each isotope multiplied by its dose equivalence factor:

$$PE\text{-}Ci = \Sigma\,(\text{dose equivalence factor})_n \times (\text{curies})_n \text{ for } n \text{ isotopes} \qquad \textbf{Equation 6.2-11}$$

In the case of Pu-239, dose equivalence is a method of normalizing the radiotoxicity of various radionuclides to Pu-239 for use in determining relative hazard of radioactive materials. The normalization is often based on the inhalation pathway only. It is derived from the ratio of the relative adult inhalation committed effective dose for each radionuclide to that of Pu-239 using the inhalation dose conversion factors from ICRP-72, *Age-Dependent Doses to Members of the Public from Intake of Radionuclides, Part 5*. This ratio is the dose equivalence factor of the isotope per curie of isotope.

7 CHEMICAL DISPERSION AND CONSEQUENCE ANALYSIS

7.1 INTRODUCTION

Chapter 6 discussed radiological dispersion and consequence analysis with its main focus on radiological releases. Many of the atmospheric dispersion principles associated with radiological releases of neutrally-buoyant gases discussed in Chapter 6 are also applicable to neutrally-buoyant toxic chemical releases. Wherever there was commonality between radiological and toxic chemical dispersion and consequence analysis, it was so indicated in that chapter.

There are many types of toxic chemical releases that require a more comprehensive treatment than steady-state releases of neutrally-buoyant gases. These analyses involve more specialized source term phenomenological models and atmospheric dispersion models to address their emission into and redistribution in the atmosphere. In addition, the human health effect metrics of toxic chemicals are far more complex than the metrics associated with radiological health effects. Each of these differences are identified and treated in this chapter and subsequent chemical dispersion and consequence analysis appendices.

DOE-STD-3009-2014 requires assessment of toxic chemical hazards as part of a DSA, in both hazard and accident analyses. DOE has also included formal chemical consequence criteria in DOE-STD-1189-2008, Appendix B.

As in Chapter 6, this chapter addresses the evaluation of releases of toxic chemicals and associated concomitant health risks to the facility worker, CW, MOI and the public. However, it discusses the different types of chemical release phenomenology and the factors to consider when estimating the health effects that these toxic chemicals can have on the human body and its target organs. Once the toxic chemical source term phenomenology is established and the appropriate atmospheric dispersion model selected, the resultant health risks associated with each toxic chemical needs to be evaluated at each important receptor and compared to the appropriate chemical health indicators.

NSRD-2015-TD01, Technical Report for Calculations of Atmospheric Dispersion at Onsite Locations for Department of Energy Nuclear Facilities, concluded:

> *"Similar to calculations for the radiological releases, the chemical release calculations showed that the default χ/Q value is conservative for chemical releases for nearly all cases, except the situations where the building wake cannot be credited or where a building is smaller than that assumed in NUREG-1140. For these situations the default χ/Q value may not provide a conservative estimate of dispersion."*

This chapter addresses both the dispersion of chemical materials and their consequences in terms of exposure concentrations to meet the requirements of Section 3.2.4.3, Chemical Dose Consequence, of DOE-STD-3009-2014 once the source term (ST) either as a release rate (mg/s) or total release quantity (mg) over a release duration is estimated as described in Chapter 5. For safety analysis purposes, the dispersion analysis is used to estimate chemical consequences in terms of a peak air concentration that occurs any time during the duration of the release to the MOI or CWs.

The general approach for the atmospheric dispersion and chemical consequence analysis is:

1. From the accident scenario as defined by applying Chapter 3 guidance, identify parameters relevant to evaluating releases to the environment, e.g., ground level, buoyant, elevated stack, discharge temperature, etc.
2. Select the appropriate dispersion methodology (e.g., a DOE Toolbox code or manual spreadsheet calculations).
3. Analyze appropriate weather data and convert to a format for the selected methdolology.
4. Apply the dispersion methodology, justifying input values as affected by the accident scenario, unique site conditions, or recommended default values from the most recent guidance documents, such as those for the DOE Toolbox codes or this chapter.
5. Calculate the chemical concentration to the MOI and co-located workers.

This Chapter goes through each of these steps. However before doing so it begins with some fundamentals of chemical consequence assessment and other topics that support the DSA analysis of chemicals. Specifically this Chapter provides information on:

- Chemical Consequence Assessment Fundamentals;
- Chemical Screening Criteria;
- Chemical Health Effects on the Human Body;
- Toxic Chemical Release Phenomenology;
- Atmospheric Transport And Diffusion;
- Meteorological Parameters Affecting Consequence Analysis;
- Toxic Chemical Atmospheric Transport and Diffusion Models;
- A Scoping Methodology; and
- Example Calculations.

7.2 CHEMICAL CONSEQUENCE ASSESSMENT FUNDAMENTALS

There are a number of ways in which the consequence assessment of toxic chemicals differ from that of radioactive materials; thus requiring more comprehensive treatment. The most fundamental difference is that unlike radiological exposures whose health effects have been normalized to a common scale of rem measurement, each particular toxic chemical insults the human body in its own unique way; enormously complicating the health effects evaluation portion of the assessment process. For a facility with an inventory of many different chemicals, consequence assessment can quickly become a cumbersome process. Accordingly, chemical hazard assessment makes extensive use of a screening process to focus on those chemicals of sufficient quantity and toxicity to present a clear potential threat to the facility worker, co-located worker and public. Without this screening process, the amount of effort to perform chemical consequence assessments would be untenable.

Toxic chemical impacts also differ from radioactive material impacts in that the adverse health effects induced by the former are typically associated with a threshold dose or concentration, usually defined for most toxic chemicals below which no adverse effects are expected. In contrast, the effects elicited by radioactive materials on the human body are assumed to occur over a dose continuum. Chemicals that have chronic carcinogenic, mutagenic and teratogenic effects, similar to those of radioactive materials, are considered non-threshold events.

Other consequence assessment differences include the physical and temporal characteristics associated with the release phenomenology, the atmospheric characteristics of the plume, and the nature of the health and environmental effects. For chemicals that have a higher molecular weight than that of the atmosphere (i.e., 28.97 g/mol), density differences can result in dense gas gradients, resulting in airborne plumes that remain near the ground and flow downhill in response to local topography. In addition, chemicals that are physically much colder than the environment (i.e., cryogenic) may also exhibit dense gas characteristics. Lastly, the quantity of the release is another important discriminator, as the release has to be sufficiently large to create its own dense gas dispersion environment. The Bulk Richardson number is used by dense gas models (e.g., ALOHA) to determine the nature of the dispersion environment. NRSD-2015-TD01 Section F.6 and Section 7.5.3 of this Handbook present additional discussion on dense gas dispersion. Chemical reactions in contact with air and upon exposure to sunlight atmospheric moisture can also alter the human toxicity characteristics of a plume by changing its chemical composition and concomitant health effects. To further confound chemical consequence assessment, chemicals differ in ultimate health impacts depending on whether their toxicity is concentration-dependent based or dose-dependent based. Chemicals, for which the toxicity effect is immediate, or acute, are considered to be concentration-dependent.

7.3 CHEMICAL SCREENING CRITERIA

The evaluation of toxic chemical hazards at a DOE/NNSA facility often involves the consideration of many chemical substances. The DSA can be simplified with a negligible loss in conservatism and scientific integrity by limiting the toxic chemical hazard evaluation to toxic chemicals that constitute the most significant safety concerns. This simplification can be accomplished through a systematic chemical pre-screening process. DOE-STD-3009-2014 Appendix A Section A.2 provides the most recent chemical screening guidance for DSA hazard evaluations such as excluding chemicals that are commonly available and used by the general public, or small-scale use quantities of chemicals. The following discussions provide additional clarifications and guidance related to the toxicity guidance addressed in DOE-STD-3009-2014 Appendix A Section A.2.

The factors that determine the degree of hazard that any given chemical represents include:

- Physicochemical properties that contribute to dispersibility, reactivity, and toxicity;
- Incompatibility with other chemicals; and,
- Conditions under which the chemical is stored and/or used, including the quantity involved.

Specific questions to determine which chemicals to include in a DSA are presented in Table 7-1.

Table 7-1. Identification of Chemicals in the Prescreening Process: Baseline Criteria.

A) Is a particular chemical on any of the following lists?
• EPA list of extremely hazardous substances and threshold planning quantities (40 CFR. 355)
• EPA list of hazardous substances and reportable quantities (40 CFR 302)
• OSHA list of highly hazardous chemicals, toxic chemicals and reactive chemicals (29 CFR 1910.119(e))
• EPA list of regulated substances and thresholds for accidental release prevention Threshold Quantities (40 CFR 68)
B) Have any short-term acute exposure limits been derived for a particular chemical?
• EPA AEGLs
• AIHA ERPGs
• DOE/NA-41 PAC/Temporary Emergency Exposure Limits (PAC/TEELs)
C) Is there any indication that the particular chemical exhibits significant toxic properties in Safety Data Sheets (SDSs), required by OSHA Hazards Communication, 29 CFR 1910.1200?
D) Is a particular chemical extremely reactive or flammable with a National Fire Protection Association (NFPA) Health Hazard Rating (HHR) of 3 or 4? See DOE-STD-3009-2014 Section A.2.
E) Is a particular chemical in close physical proximity to other incompatible chemicals, which could result in the release of toxic reaction products in an accident?
F) Is a particular chemical readily volatilized (i.e., having a high vapor pressure) upon release to the atmosphere?
G) Does a particular chemical generate toxic combustion products?
H) Does a particular chemical act as a simple asphyxiant which reduces the available oxygen below 19.5 percent, per OSHA 29 CFR 1926.55 Appendix A? Additional simple asphyxiant guidance is provided in ANSI Z88.2-1992 and DOE-HDBK-1046-2008.

SDSs are required from chemical manufacturers to meet OSHA 29 CFR 1910.1200 hazard communications requirements. These also provide valuable chemical exposure health effects information relative to chemical screening, as follows:

- Section 2: Hazards identification inclusive of target organs, routes of entry, acute effects, chronic health effects, carcinogenic, mutagenic and teratogenic effects;
- Section 10: Stability and reactivity; and
- Section 11: Toxicological information.

All chemicals that are not screened out have to be evaluated in DSAs to ensure that unmitigated consequences to the facility worker, CW, MOI, and the public do not exceed the EGs.

7.4 CHEMICAL HEALTH EFFECTS ON THE HUMAN BODY

A key premise in analyzing chemical consequences is that chemical consequence PAC[38] are based on chemical concentration, while radiological PACare based on integrated committed dose to all target organs. Therefore, the physiological impact of chemical exposure is inherently different from radiological exposure. The following subsections address chemical concentration, exposure modes and exposure time, and the various PACs to establish acute human health effects. In addition, chronic chemical exposure effects are briefly addressed. DSAs only require the assessment of the acute effects of toxic chemicals.

7.4.1 CHEMICAL CONCENTRATIONS AND EXPOSURE TIME

7.4.1.1 CHEMICAL EXPOSURE TIME

Chemical exposure concentrations may be expressed in either units of mg/m^3 or parts per million volume (ppmV). The latter represents a volume ratio of parts of toxic chemical per million parts of clean air, while mg/m^3 units are commonly used for aerosol release (i.e., particulates or droplets of non-volatile liquid) evaluations. For releases involving gases or vapors from volatile liquids, units of mg/m^3 can be used but ppmV units are more commonly used. Equation 7.4-1, which is based on the equation of state of an ideal gas, can be used to convert concentrations in units of mg/m^3 to units of ppmV, assuming a standard pressure of one atmosphere (101,325 N/m^2) and ambient temperature of 25 °C; the latter recommended in 40 CFR 68.22.

$$\mathbf{C}[ppm] = \mathbf{C}[mg/m^3(\text{air})] \times \mathbf{10^6}\ [\text{m}^3(\text{air})/10^6\ \text{m}^3(\text{air})] \times \left\{ \frac{\mathbf{R} \times \mathbf{T}}{\mathbf{MW} \times \mathbf{P} \times \mathbf{1000}} \right\} [m^3/mg]$$

Equation 7.4-1

38 PAC values for emergency planning for chemical release events are based on the following exposure limits, given in terms of airborne concentration, expressed as ppm or mg/m^3:
1. AEGL values published by the U.S. Environmental Protection Agency (EPA);
2. Emergency Response Planning Guideline (ERPG) values produced by the American Industrial Hygiene Association (AIHA);
3. TEEL values developed by the DOE Subcommittee on Consequence Assessment and Protective Actions (SCAPA).

AEGLs, ERPGs, and TEELs have three common benchmark values for each chemical (i.e., PAC-1, -2, and -3). Each successive benchmark is associated with an increasingly severe effect that involves a higher level of exposure. The DOE policy for its facilities and activities established irreversible health effects (the "-2" level) as the protective action criterion benchmark for chemical releases. ERPGs refer to exposure durations of 1 hour (with shorter periods for some chemicals). While AEGLs are developed for five time periods the PAC database includes the AEGL one-hour value. TEELs will be standardized on one-hour in the near future, but are now based on 15-minute TWAs. PAC values are developed to take into account all factors potentially causing a human health affect caused by exposure to the defined chemical. Refer to http://orise.orau.gov/emi/scapa/chem-pacs-teels/default.htm.

Where,

10^6	=	ppmV conversion factor [units of "m^3(air)/$10^6 \cdot m^3$(air)"]
R	=	Universal gas constant [8.314 N·m/gmol·°K]
MW	=	Molecular weight [g/gmol]
P	=	Standard atmospheric pressure [101,325 N/m^2]
T	=	Temperature [°K]
1000	=	Mass conversion factor [units of "mg/g"]

The term enclosed by the large brackets represents the specific volume (i.e., reciprocal of density) of the chemical, which is directly proportional to ambient temperature.

Chemical health impacts are based on total exposure, which is a function of both the chemical concentration at the receptor and the amount of time this chemical concentration is received (i.e., exposure duration). Ten Berge (1986) developed a technique to account for exposure time on dose, and the Areal Locations of Hazardous Atmospheres (ALOHA) toolbox code has an algorithm that calculates dose as a function of exposure time using ten Berge's equations. Exposure time is an important factor in considering the relative significance of any exposure for dose-dependent chemicals, and for some cases, concentration-dependent chemicals.

Averaging time is discussed further given its importance in chemical consequence assessments. The toxicity characteristics of the chemical and duration of the plume exposure both factor into the time basis for the TWA. Plume exposure duration and toxicity characteristics can be appropriately addressed, as follows:

Plume Exposure Duration - The plume exposure duration is generally assumed to be the same as the release duration (i.e., Δt) of the source term. DOE-STD-1189-2008, Appendix B recommends that 1 minute be used as the minimum time basis if the release duration is less than 1 minute.

For hazardous chemical aerosols and gases with a density near that of air, standard Gaussian atmospheric dispersion may be used to estimate chemical consequences. If the toxic material is released at some average rate over some period of time, the peak concentration at the receptor is obtained directly from the definition of the steady state χ/Q

$$\mathbf{C = Q'\left(\frac{\chi}{Q'}\right)} \qquad \textbf{Equation 7.4-2}$$

Where,

C = peak concentration (mg/m^3)
Q' = toxic material release rate (mg/s)
χ/Q = relative concentration (s/m^3)

Some consequence assessment dispersion codes will calculate the desired maximum 15-minute average concentration directly by allowing the analyst to specify the averaging period. To determine the average concentration manually, the following formula may be used:

$$\mathbf{TWA} = \frac{C_1T_1+C_2T_2+C_nT_n}{T_1+T_2+T_n} \qquad \textbf{Equation 7.4-3}$$

Where:

C = Concentration (ppm or mg/m^3)
T = Time period of exposure (min)

7.4.1.2 CONCENTRATION-DEPENDENT VS. DOSE-DEPENDENT CHEMICALS

Chemical toxicity characteristics are broadly classified among two groups; (1) concentration-dependent chemicals; and, (2) dose-dependent chemicals:

- Concentration-dependent chemicals are those whose toxic effects correlate more closely to a threshold concentration, than to a time-integrated exposure (i.e., dose); and,
- Dose-dependent chemicals are those whose toxic effects depend upon the total amount of material taken up by the body.

For concentration-dependent chemicals, at least the initial concentration estimates should be baselined to a peak 15-minute TWA for comparison with measures of significance. For dose-dependent chemicals, a peak 1-hour average concentration is generally recommended. If the toxic effects of a chemical are known to be dose-dependent (i.e., the toxic effects depend upon the total quantity of material taken up by the body) and not concentration-dependent, then for these chemicals only, the 1-hour average concentration may be used.

For short-duration releases (e.g., less than 15 minutes), the concentration at the receptor may be calculated as the Time Weighted Average (TWA) over the release period, but for no less than 1 minute. Since concentration varies with time due to time-dependent release rate (Q') and long-wave atmospheric turbulence (i.e., plume meander), concentrations based on one-minute segments do not credit plume-meander; consistent with the concept of determining a peak TWA that is not smeared by time averaging effects.

Table 7-2 shows the relationship between release duration and time basis for establishing Time Weighted average (TWA) for both concentration-dependent and dose –dependent toxicity characteristics.

Table 7-2. Time Basis for TWA.

Toxicity Characteristic	Release Duration	Time Basis for TWA
Concentration-Dependent	**$\Delta t \leq 15$ minutes**	**Δt (or 1 minute if $\Delta t \leq 1$ minute)**
	$\Delta t > 15$ minutes	**15 minutes***
Dose-Dependent	**Any Δt**	**1 hour****

* The 15-minute segment that produces the highest consequences should be used.

** The 1-hour segment that produces the highest consequences should be used.

For release durations longer than 15 minutes, the peak 15-minute average concentration during the duration of the release is used for concentration dependent chemicals. For the peak 15-minute TWA, the 15-minute period of maximum exposure (concentration) is selected and input (as 15, one-minute segments) into Equation 7.2-2. For exposure periods of less than 15 minutes, the product of C_xT_x may equal zero during the exposure period. Individual time intervals less than one minute are not appropriate for use in the numerator of the above formula for calculating the TWA. This assumption is conservative for "instantaneous" types of releases (e.g., container puncture of powders, over-pressurization of container). However, the use of a shorter averaging duration than 15 minutes, such as the actual exposure period but not less than one minute, may be warranted depending on the acute toxicity of the chemical of interest and the peak concentration observed.

7.4.1.3 PROTECTIVE ACTION CRITERIA (PAC) FOR RELEASES OF A SINGLE CHEMICAL

Exposure to an air concentration greater than the toxic PAC criteria for safety SS control selection is assumed to confer a certain health detriment to the exposed individual. Although a duration of exposure is implicit in the PAC definitions, shorter exposures to higher concentrations of some chemicals can have comparable effects. Accordingly, averaging the concentration from a short-duration release over 30 or 60 minutes may significantly under-predict the hazard. On the other hand, averaging over a very short time (e.g., a minute or two) represents the peak concentration more conservatively; however, the validity of any comparison between the calculated "peak" concentration PAC value is questionable. It is therefore useful to calculate a TWA concentration at the receptor location for some period less than that implied by the PAC definition but long enough that the results can be viewed as having relevance to the criteria.

To address both concerns, TWA concentration at the receptor location is usually calculated for some period less than that implied by the PAC definition, but long enough that the results can be accepted as having some relevance to the criteria. For example, EPA-550-B-99-009, *EPA Risk Management Program Guidance for Offsite Consequence Analysis*, which specifies ERPG-2 values (one of the criteria for establishing the PAC-2) as primary toxic endpoints for their evaluation, assumes a 10-minute release averaging time in its determination of distance to the endpoint for worst-case analyses of toxic gases even though the ERPG-2 values are based on 60 minutes.

The DOE PAC concentrations are based on different durations as defined by their concentration limit definitions from EPA or chemical industry. To standardize releases from gases, liquids, and particulates, the hazard evaluation and/or accident analysis may assume a peak 15-minute, TWA chemical concentration for comparison to the PAC values for SS control designation. There is no adjustment of the PAC value or the calculated concentration to account for differences between the recommended 15-minute exposure time and the exposure time implicit in the definition of the PACs.

7.4.1.4 PROTECTIVE ACTION CRITERIA (PAC) FOR RELEASES OF MULTIPLE CHEMICALS

For chemical mixtures and concurrent releases of different substances, consequences are assessed using the Mixture Methodology "Hazard Index" approach recommended by the DOE Office of Emergency Management SCAPA Chemical Mixtures Working Group. A brief explanation of this approach and the published journal article are available on the SCAPA website, http://www.orau.gov/emi/scapa/index.htm, under Health Code Numbers. An Excel workbook that automates the implementation of the approach and its user's guide are also available on the SCAPA website.

Concurrent releases are analyzed if a plausible scenario exists by which quantities of different substances could be released from the same location at the same time. Concurrent releases of dissimilar substances

that, because of separation by distance or physical barriers, could result only from extreme malevolent acts or catastrophic events (such as major fires, airplane crashes, severe natural phenomena impacts, and building collapse) need not be analyzed.

7.4.2 MODES OF EXPOSURE AND ROUTES OF ENTRY OF TOXIC CHEMICALS THAT RESULT IN HEALTH EFFECTS

Acute health effects from short-term exposures to toxic chemicals differ with respect to mode of exposure (MOE) or route of entry (ROE) into the human body. Since the inhalation pathway is also considered the most impactful for toxic chemical exposures, most toxic chemical consequence assessments focus on inhalation exposures. Impacts from chemical ingestion are generally chronic in nature and can be prevented by water and food interdiction management measures or mitigated by chelation processes.

DOE-HDBK-1046-2008, "*Temporary Emergency Exposure Limits for Chemicals: Methods and Practice*," provides an excellent discussion on all MOEs and ROEs and also discusses each pathway inclusive of inhalation, skin absorption, inter-peritoneal, ingestion, etc., associated with acute effects of chemicals on human health. These form the toxicological basis for the PAC/TEELs. This Handbook also provides an excellent discussion on which organs are targeted by specific chemicals from the Health Indices (HIs) and Health Code Numbers (HCNs) of the Chemical Mixture Methodology (CMM). The CMM can be used if the analysis involves the release of up to 30 chemicals.

7.4.3 TOXIC CHEMICAL ACUTE EXPOSURE LIMITS

There are three types of PACs available to the analyst: (1) AEGLs for 8 different exposure periods developed by EPA for about 300 specific chemicals; (2) ERPGs for about 150 substances for an approximate one-hour exposure period developed by the AIHA; and, (3) PAC/TEELs developed by the DOE Office of Emergency Response and Policy Implementation (DOE/NA-41) for 3386 specific chemicals. The PAC/TEELs represent the most comprehensive compendium of acute exposure guidelines, and Revision 27, issued in February 2012 can be accessed at http://www.atlintl.com/DOE/teels/teel.html. For chemicals that are not toxic, but can act as simple asphyxiants at high concentrations that reduce ambient oxygen to levels where human health can be compromised, the PAC/TEELs for that chemical establishes concentrations that will result in various levels of human health insult and incapacitation:

- PAC/TEEL-1 represents a concentration where oxygen levels are reduced to 19.5%; the OSHA limit for respiratory protection;
- PAC/TEEL-2 represents a concentration where oxygen levels are reduced to 16%. At this level, a threshold is reached for the onset of impaired coordination, perception, and judgment; sufficient to compromise a person's ability of self-protection and escape; and
- PAC/TEEL-3 represents a concentration where oxygen levels are reduced to 12.5%, the threshold for causing very poor judgment and coordination, followed by unconsciousness and death.

DOE-HDBK-1046-2008 documents the process of how the PAC/TEELs were developed and how they should be applied.

7.4.3.1 EPA ACUTE EXPOSURE GUIDELINE LEVELS (AEGLS)

EPA's Office of Prevention, Pesticides and Toxic Substances established the National Advisory Committee for Acute Exposure Guideline Levels (NAC/AEGL Committee) for Hazardous Substances to develop AEGLs. They are intended to assist Federal and State Agencies and private sector organizations with their needs for short-term hazardous chemical exposure information.

In the final Clean Air Act (CAA) Amendments, Section 112 Risk Management rulemaking (June 20, 1996, 61 FR 31685 [FRL-5516-5]), it was stated, "EPA recognizes potential limitations associated with the ERPGs and Levels of Concern and is working with other agencies to develop AEGLs." When these values have been developed and peer-reviewed, EPA intends to adopt them, through rulemaking, as the toxicity reference for substances under this rule (FR 1997).

Final and interim AEGLs for about 300 chemicals have been published and are essentially comparable to ERPGs, with AEGL-1 labeled "non-disabling," AEGL-2 labeled "disabling," and AEGL-3 labeled "lethality."

The principle advantage of AEGLs is that they are given for 8 exposure times ranging from 10 minutes to 8 hours. The disadvantage is that they are available for a limited number of chemical substances.

7.4.3.2 AIHA EMERGENCY RESPONSE PLANNING GUIDELINES

The AIHA began developing ERPGs for use in evaluating the health effects of accidental chemical releases on the general public. These ERPGs are developed and published annually through a rigorous peer review process conducted by the AIHA Emergency Response Planning (ERP) Committee. The ERPG development process results in high-quality community exposure limits that are recognized and used both nationally and internationally.

ERPGs have been published for approximately 130 chemicals. For specific chemicals, ERPGs are estimates of concentration ranges above which acute exposure would be expected to lead to adverse effects.

- ERPG-1: The maximum airborne concentration below which it is believed that nearly all individuals could be exposed for up to 1 hour without experiencing other than mild transient adverse health effects or perceiving a clearly defined objectionable odor.
- ERPG-2: The maximum airborne concentration below which it is believed that nearly all individuals could be exposed for up to 1 hour without experiencing or developing irreversible or other serious health effects or symptoms that could impair their abilities to take protective action.
- ERPG-3: The maximum airborne concentration below which it is believed that nearly all individuals could be exposed for up to 1 hour without experiencing or developing life-threatening health effects.

7.4.3.3 DOE/NA-41 PAC/TEELS

Many of the chemicals of interest at DOE/NNSA sites lack ERPGs and AEGLs. In response to this need, DOE Office of Emergency Response and Policy Implementation developed a TEEL methodology in 1992 to provide interim guidance for chemicals of interest. TEEL-1, TEEL-2, and TEEL-3 have the same definitions as the equivalent ERPGs and one-hour AEGLs. Time of exposure issue has been removed in TEEL use by recommending the peak 15-minute TWA as the value of comparison.

The methodology for assigning TEELs was originally based on hierarchies of commonly available published and documented concentration-limit parameters, particularly occupational exposure limits, later expanded to include other published concentration limits and then further expanded to include the use of published toxicity parameters. The current TEEL hierarchy is listed in Table 7.4-2. Table 3.1 of DOE-HDBK-1046-2008 shows a similar hierarchy for the AEGL3, AEGL-2 and AEGL-1 values.

Table 7-3. TEEL Hierarchy and Toxicity Methodology.

Primary Guideline	Hierarchy of Alternative Guidelines for TEEL-i	Source of Concentration Parameter
ERPG-3	TEEL-3: Emergency Exposure Guidance Level (EEGL) (30-min) Immediately Dangerous to Life and Health (IDLH) Lethal Concentration for 50% (LC_{50}) Lethal Concentration Lowest (LC_{LO}) Lethal Dose for 50% (LD_{50}) Lethal Dose Lowest (LD_{LO})	AIHA 1999 NAS 19854 NIOSH 1997
ERPG-2	TEEL-2: EEGL (60-min) Level of Concern (LOC) Permissible Exposure Level (PEL-C) Threshold Limit Value (TLV-C) Recommended Exposure Limit (REL-C) Workplace Environmental Exposure Limit (WEEL-C) Threshold Limit Value – Time Weighted Average (TLV-TWA) x 5 Toxic Concentration Lowest (TC_{LO}) Toxic Dose Lowest (TD_{LO})	AIHA 1999 NAS 1985 EPA 1987 CFR 29:1910.1000 ACGIH 1999 NIOSH 1997 AIHA 1999 ACGIH 1999
ERPG-1	TEEL-1: Permissible Exposure Level-Short-Term Exposure Limit (PEL-STEL) Threshold Limit Value – Short-Term Exposure Limit (TLV-STEL) Recommended Exposure Limit - Short-Term Exposure Limit (REL-STEL) Workplace Environmental Exposure Limit - Short-Term Exposure Limit (WEEL-STEL) other-STEL TLV-TWA x 3	AIHA 1999 CFR 29:1910.1000 ACGIH 1999 NIOSH 1997 AIHA 1999 e.g., German, Russian ACGIH 1999

7.4.4 CHEMICAL MIXTURE METHODOLOGY

Effects from exposure to multiple chemicals can be addressed by using the CMM, also developed by the DOE Office of Emergency Response and Policy Implementation. The CMM approach determines whether effects of multiple chemicals are synergistic or antagonistic on various target organs.

The CMM provides recommended default emergency exposure guidelines for mixtures of chemicals. The CMM makes extensive use of HCNs to examine the additive impact that each chemical component in a chemical mixture may have on specific target organs. The CMM is a more realistic predictor of potential human health impacts than can be obtained using the:

(1) Non-conservative method of separately analyzing the consequences of each chemical component; or,
(2) Overly-conservative method of adding the exposures from each chemical together regardless of the human organ targeted by the chemical.

The CMM is recommended for potential use in emergency planning hazards assessments (EPHAs), DSAs, and in emergency response situations. The CMM and its workbook can be downloaded from http://orise.orau.gov/emi/scapa/chem-mixture-methodolgy/default.htm .

The CMM approach that involves adding all exposures from each chemical, regardless of the target-organ effects of the chemicals, tends to overestimate impacts and therefore be over-conservative. The health impacts from chemicals that target different organs are often not simply additive to all target organs.

When using the CMM, a hazard index (HI) is calculated for each component of a chemical mixture at the chosen receptor point. The "HI_i" is the concentration of chemical "i" ($Conc_i$) divided by the concentration limit for chemical "i" ($Limit_i$), as shown in Equation 7.4-2:

$$HI_i = Conc_i/Limit_i \qquad \textbf{Equation 7.4-4}$$

A $HI_i < 1$ means that the limit for that single chemical "i" has not been exceeded. However, if the hazard indices for all chemicals in a mixture are summed, and the cumulative hazard index is greater than one, then an unacceptable condition may exist and mitigating strategies may need to be considered. Unless the health effects of the components are known to be independent, the toxic consequences of all components should, as an initial step in an assessment, be considered to be additive. This represents the most conservative upper-bound approach for assessing exposures to mixtures. If this upper-bound approach produces unacceptable results, the next step is to classify the chemicals in the mixture according to their toxic consequences. The toxicological classification of specific chemicals can be accomplished using the HCNs established for each chemical.

HCNs are used in the CMM to identify the target-organ effects of each chemical in the mixture. Any chemicals that targets the same or similar organs or operates by the same acute or chronic mode of toxicity should be considered additive to that target organ or by that same mode of toxicity. Target-organ effects and modes of toxicity are considered simply as target organ effects.

HCNs are similar to medical diagnostic codes in that they are code numbers that identify a particular target organ or health effect to enable classification of chemicals by target organ toxicity. Summation of HIs for all chemicals in a mixture having the same toxic consequences (i.e., same or similar HCNs) enables determination of the acceptability or unacceptability of exposure to any specific mixture of chemicals using this more realistic approach.

HCNs also offer a convenient way of performing this exposure addition by numerically "binning" identical or similar target-organ effects. All of the individual exposure HIs that are binned into the same or similar HCN bin are added together to yield an "HI sum" for that target-organ bin. Any of the individual HI sums that exceed a value of 1.0 indicate that the exposure limit has been exceeded and that some kind of mitigating action should be taken to reduce the exposure to that specific target organ below the applicable limit.

The latest version of the CMM Workbook, which can process up to 30 chemicals in a given mixture, is in CMM Revision 27.

7.4.5 CHRONIC HEALTH EFFECTS OF TOXIC CHEMICALS ON THE HUMAN BODY: CARCINOGENICITY, MUTAGENICITY, AND TERATOGENICITY

Although DOE has a few large inventories of carcinogenic chemicals, DOE DSAs do not typically evaluate carcinogenic effects but focus on documenting consequences of chemicals with acute exposure effects. The DOE Safety Goal related to latent cancer fatalities (LCFs) for radiological releases is with respect to 50-mile radius population doses and not to the facility worker, CW, or MEI. There is no analogous DOE Safety Goal associated with carcinogenic chemicals. The following provides some information on where to obtain chronic chemical health effect information.

Dose-response curves for non-carcinogenic chemicals are characterized by the existence of threshold exposure levels below which no toxic effects will be observed. Due to a fundamental difference in the mechanism of action, the dose-response curves for carcinogens are considered as linear, no-threshold (NLT) representations.

Known or suspected human carcinogens are identified in the EPA data bases Integrated Risk Information System (IRIS) and Health Effects Assessment Summary Tables (HEAST), the National Institute for Occupational Safety and Health (NIOSH) Pocket Guide to Chemical Hazards, and International Agency for Cancer Research (IACR) publications.

Per 1986 EPA guidance, confirmed or suspected human carcinogens are treated differently from those compounds eliciting only acute toxic effects. Incremental cancer risk (ICR) can be calculated using the IRIS database values for the chemical-specific slope factor.

7.5 TOXIC CHEMICAL RELEASE PHENOMENOLOGY AND SUBSEQUENT ATMOSPHERIC TRANSPORT AND DIFFUSION

Unlike radiological releases, which are generally assumed to be continuous and of the same magnitude throughout the accident sequence, there are a large number of variables that need to be accounted for to characterize toxic chemical releases and their effects on the facility worker, CW, MOI, and the public. Phenomenological release, as described in Chapter 5, and special atmospheric transport and diffusion considerations that are specific to the release of toxic chemicals include, but are not limited to:

- Temperature, pressure, and state of the chemical in its storage container;
- Type of storage container (e.g., tank, vessel, pipe);
- Density, temperature and quantity of the toxic chemical released that determines whether it will disperse as a positively-buoyant gas, neutrally-buoyant gas, or a dense or heavy gas;
- Phenomenology of toxic chemical release (e.g., guillotine break of a pipe, small hole (i.e., orifice) in a tank or pipe, break in a tank with a connecting pipe);

- Speed of chemical release leaving its container through an orifice relative to the speed of the sound (i.e., choked flow versus non-choked flow);
- Energy associated with the toxic chemical release, which includes fire, deflagration, detonation, delayed ignition detonation, or BLEVE;
- Chemical transformations resulting from the effects of a fire (e.g., oxidation) or chemical reaction with water vapor in the atmosphere (e.g., release of uranium hexafluoride to a humid atmosphere); and,
- Synergistic and antagonistic effects of a multiple chemical release and the cumulative effects on target organs, which was addressed in Section 7.4.4.

The following subsections present a brief discussion on toxic chemical release phenomenology. A more extensive treatment can be found in Appendix G.

7.5.1 PRESSURIZED LIQUIDS: TWO-PHASE FLOW TOXIC CHEMICAL RELEASE

Pressurized liquid releases are the most complex of non-energetic single chemical releases, as two-phase flow needs to be accounted for. The initial portion of the liquid release flashes to a gas, due to its rapid depressurization at the point that it encounters the atmosphere. The flashed portion of this type of release is usually of short duration (i.e., a puff) which requires a three-dimensional Gaussian puff model to determine its fate and transport.

The remaining chemical that does not flash forms a liquid puddle, or gaseous area source for a sublimating chemical (e.g., carbon dioxide). The liquid puddle evaporates as a non-pressurized sub-cooled liquid release behind the puff requiring a conventional two-dimensional Gaussian code similar to what would be used on a liquid evaporative release. This evaluation may also need to be performed in an iterative manner since the source term varies with time.

Pressurized liquid releases from a tank through a pipe adds one additional level of complexity as the rapid depressurization of the chemical when it reaches the atmosphere at the point of the pipe break causes a choked flow condition, discussed in Section 7.5.2, upstream of the pipe. Thus, the flashing of the liquid occurs inside the pipe before discharge, and this choked flow limits the mass release rate. Analysis of this phenomenology is a highly complex time-dependent process as the fluid near the discharge experiences a pressure drop and flashes, while the fluid upstream does not sense the break and stays in liquid form. Therefore, an oblique pressure wave travels upstream resulting in a greater fraction of the liquid flashing inside the pipe. For this type of chemical release, the Vapor Mass Fraction (VMF) needs to be calculated in an iterative manner to determine the time-varying chemical source term. Therefore, the analyst accounts for the phenomenology of pressurized liquid releases using techniques such as those in Appendix G.

The Hazard Prediction and Assessment Capability (HPAC) ITRANS source term module provides a comprehensive methodology to establish chemical release quantities; especially for pressurized liquid chemical releases. HPAC has dense gas modeling capabilities, and a sub-code, Second-Order Closure Integrated PUFF (SCIPUFF) (Sykes, 1996), that can also address positively-buoyant gases quantifying its liftoff after release.

7.5.2 PRESSURIZED GASES: CHOKED FLOW TOXIC CHEMICAL RELEASE

The release of pressurized gases is either under choked flow or non-choked flow depending on the internal pressure and the size of the orifice; both of which affect the speed at which the gas escapes through the orifice.

Pressurized gaseous non-energetic single chemical releases (e.g., hole in a cylinder containing gas stored at several atmospheres pressure) also cannot be addressed by steady-state Gaussian models since the source term is never steady-state; always varying with time. This is the result of the internal pressure decreasing with time as the gas escapes through the orifice and the remaining unreleased gas undergoing Joule-Thompson cooling, which affects its temperature and volume. As the internal pressure decreases with time, the release rate will decrease accordingly.

For highly-pressurized gases that are released through a very small orifice, additional complexities associated with choked flow need to be accounted for. Choked flow occurs when the released gas attempts to exit its storage container at a rate that exceeds the speed the sound, which itself is a function of ambient temperature. Accordingly, a gas cannot travel outside of its containment at a speed greater than the speed of sound, which is a physically limiting factor. Therefore, the analyst accounts for choked flow, using techniques such as those in Appendix G, until the internal pressure is reduced to a subsonic level, where the flow becomes and remains non-choked. Pressurized gases escaping through an orifice at speeds less than the speed of sound will do so under non-choked flow.

ALOHA Version 5.4.4 incorporates LEAKR algorithms (Belore and Buist 1986) to establish the release rate of gases from orifices, holes and short pipes. It initially determines whether gas flow will be supersonic (i.e., choked) or subsonic (i.e., unchoked) from the ratio of tank to atmospheric pressure, ratio of hole width to tank length, and critical pressure ratio for sonic flow. Should the pressure difference be large enough, ALOHA models flow as supersonic until the pressure drops to the point at which flow reaches subsonic speeds. From that point onward, ALOHA computes a subsonic release rate tank pressure which has been reduced to atmospheric pressure. The estimated rate of gas release gets smaller over time since tank or pipe pressure is expected to drop as gas exits and adiabatic expansion from Joule-Thomson cooling, cools the tank contents, further reducing pressure.

7.5.3 DENSE GAS TOXIC CHEMICAL RELEASE AND DISPERSION

Toxic chemical releases are dense or heavy gas releases when their molecular weight is greater than that of air (i.e., 28.97 g/mol for dry air), or the gas is cryogenic or very cold. Dense gas releases can potentially also occur with gases that have sufficient aerosol content. However, a gas with a molecular weight greater than that of air and/or exhibiting cryogenic properties does not always result in dense gas behavior. The dense gas blanket must be of sufficient volume to generate its own turbulence field. Therefore, the determination of whether a released material establishes a dense gas flow pattern requires the knowledge of a key parameter, the calculated Bulk Richardson number, which is a relative measure of the potential energy of the cloud with respect to the mechanical turbulent energy of the atmosphere. The Bulk Richardson number is the critical parameter that provides the benchmark for dense gas behavior. The criterion for dense gas dispersion is that the Bulk Richardson number has to be greater than 50; which is a function of volume, temperature and molecular weight of the gas relative to the gases in the atmosphere.

Initially, a dense gas cloud of material will be undiluted (i.e., not mixed with air) and will drop to the ground and flow along it downhill or in the direction of the wind, for the most part, although a small part of it may flow uphill or upwind as well, because of gravitational slumping. For this reason, an accurate

depiction of the near-field local topography is extremely important to ensure meaningful results from dense gas modeling. Vertical dispersion will be severely restricted for a dense gas, due to gravitational effects, and ambient air will be entrained through the sides of the plume. Thus, the plume shape will take on a pancake-like appearance; further distorted by local topographic anomalies.

Early models of heavy or dense gas dispersion used the Gaussian Line Source (GLS) model, in which the material was assumed to spread out from a line-source (i.e., plume), with a Gaussian distribution in the vertical and horizontal (i.e., crosswind) directions. The σ_y and σ_z values were assumed the same as given above. These models ignored many important physical phenomena, were generally unsatisfactory, and quickly fell into disuse. More modern models (e.g., DEGADIS, SLAB, HPAC, and HGSYSTEM) took into account phenomena that were not included in the GLS model. These phenomena include:

- Gravitational slumping of the heavy or dense gas and accompanying lateral spreading;
- Stratification of the heavy or dense gas, which tends to dampen turbulence and air entrainment; and,
- Heat exchange between the cloud of gas and the ground, which may also cause phase changes.

A more exhaustive discussion of the equations describing the heavy gas model and their use is beyond the scope of this Handbook. Due to the complexity of dense gas dispersion, these codes should not be used as a “black box” without a thorough understanding of the phenomena governing dense gas flows.

The analyst is recommended to use one of the standard computer codes for evaluation of heavy gas dispersion, inclusive of ALOHA Version 5.4.4. The dense gas dispersion calculations used in ALOHA are based on the DEGADIS model (Havens and Spicer 1985, Spicer and Havens 1989). DEGADIS, in turn, is an adaptation of the Shell HEGADIS model described by Colenbrander (Colenbrander 1980, Colenbrander and Puttock 1983). It also incorporates some techniques used by van Ulden (van Ulden 1974, 1983). ALOHA incorporates a decision algorithm to choose between the dense gas and neutrally-buoyant Gaussian models, using the critical Richardson's Number as the criterion for distinguishing between passive or non-passive dispersion. The critical Richardson number is a function of the density of the pollutant, the wind speed, and the release rate. Therefore, the release must be of significant magnitude to exhibit dense gas characteristics. As the dense gas plume is dispersed downwind, neutrally-buoyant ambient air begins to mix in, and when the critical Richardson number decreases to below 50, the plume begins dispersing as a neutrally buoyant gas; that is, entrainment of ambient air as the plume is transported downwind leads to the dense gas plume becoming neutrally buoyant. ALOHA then switches to the neutrally-buoyant Gaussian model. Since the entrainment of air in the sides of the plume generates significant turbulence, dense gas dispersion is actually greater than neutrally buoyant dispersion at 95-percentile meteorological conditions of F stability and 1 meter/second. This is discussed in more detail in the Technical Report NRSD-15-TC01 Section F.8 of this report presented the following conclusions relative to the CW:

1. The ALOHA χ/Q values, considering the building wake effects, are consistent with the default radiological χ/Q value specified in DOE-STD-1189-2008.

2. The aerodynamic effect of buildings on the dispersion is approximately an order of magnitude, and is much larger than the dry deposition effect;

3. The dispersion from negatively-buoyant (i.e., dense gas) releases under light wind stable meteorological conditions is greater than neutrally-buoyant releases; and,

4. The default χ/Q value is not sensitive to release durations.

Some dense gas models (i.e., HGSYSTEM, HPAC) can be used for area sources (e.g., pools) as well as line source applications.

7.5.4 NON-PRESSURIZED LIQUID RELEASE

Source term determinants from liquid releases (i.e., evaporation rate, aerosolization rate) have been addressed in detail in Chapter 3. For non-pressurized, non-energetic liquid chemical releases, it can be reasonably assumed that all aerosols immediately liquefy into the sub-cooled liquid puddle. For cryogenic non-pressurized liquids, dense gas dispersion principles still apply. The non-varying source term is commonly based on an evaporation rate, which is a function of wind speed, ambient temperature, solar insolation and an assumed puddle depth of 1 cm. This puddle depth is used in all chemical transport and diffusion codes that have evaporation algorithms and is considered a reasonable assumption by the technical community. Thus, the puddle surface area determines the amount of chemical available to be evaporated for subsequent atmospheric transport and diffusion, and this release continues until the puddle is totally evaporated.

Controls can be used to reduce the source term from this type of release. Impoundment basins allow the chemical depth to increase, thus reducing the surface area of the puddle and subsequent evaporation rate. Floating balls in such impoundment basins have also been used to further reduce the puddle surface area.

Non-pressurized, non-energetic liquid chemical releases with varying release rates cannot be as easily addressed by conventional Gaussian models since the source term can vary with time (i.e., temporally variant) as the parameters that control evaporation may vary. However, an iterative technique can be applied through successive time steps to account for varying evaporation rates while keeping the atmospheric conditions that affect transport and diffusion constant.

ALOHA Version 5.4.4 has the capacity to calculate toxic chemical consequences from non-pressurized liquid releases, employing one of two methods for finding the evaporation rate depending upon whether or not the puddle is close to its boiling point. It applies Brighton's formulation (Brighton 1985) when the average puddle temperature is sufficiently below its boiling point, and an energy balance method when the puddle approaches its boiling point. ALOHA also allows puddles to transition from boiling to non-boiling, or non-boiling to boiling. It constantly compares the evaporation rate calculated with the boiling puddle model with the evaporation rate calculated with Brighton’s model at its temperature limit, and then selects the method that yields the larger evaporation rate.

ALOHA calculates the magnitude of six energy sources to establish puddle temperature. These include:

- Net short wave solar flux into the puddle;
- Long wave radiation flux down from the atmosphere;
- Long wave radiation flux upward into the atmosphere;
- Heat exchanged with the substrate by thermal conduction;
- Sensible heat flux from the atmosphere; and,
- Heat lost from the puddle by evaporative cooling.

An example scenario for a tank release (i.e., Example 1 Part 1) is provided in ALOHA Example Scenarios (Reference: ALOHA Example Scenarios, August 2013).

7.5.5 ENERGETIC EVENTS: FIRES, DEFLAGRATIONS, DETONATIONS, DELAYED IGNITION EXPLOSIONS, AND BLEVES

For toxic chemical dispersion and consequence energetic events analysis, the initial phase of such an event releases a volume of hot gases under high pressure. Hot gases rise through its' own buoyancy and expand rapidly until reaching equilibrium with atmospheric pressure, determining the plume initial dimensions and effective height of release. After reaching equilibrium with the ambient atmosphere, conventional atmospheric redistribution processes act on this plume, carrying it downwind as it continues to expand through turbulent diffusion in the horizontal and vertical planes.

Energy associated with the release, which includes a fire, deflagration, detonation, delayed ignition detonation, and BLEVE, require special analytical treatment. A BLEVE occurs during a fire event where the contained liquid in a vessel expands due to the sensible heat transfer to the inside of the vessel and eventually reaches a point where the internal pressure from the expanding vapor in the vessel exceeds the vessel's structural integrity and a violent explosion occurs.

Few atmospheric dispersion codes in common use at DOE facilities model atmospheric dispersion from energetic events. ERAD, applicable to radionuclide releases from High Explosives (HE), has been discussed in Chapter 6.

Special techniques and codes have been developed to determine the radiant heat and other impacts resulting from fires and deflagrations. Deflagrations differ from detonations in that for deflagrations the pressure wave expands at less than the speed of sound. When chemical fires propagate at a speed that exceeds the speed of the sound, the propagation causes an overpressure in the atmosphere, which essentially moves the ambient atmosphere at a faster speed to a point downwind than it would normally move causing a compression wave, or overpressure. The detonation overpressure, which is measured in atmospheres, can be quite destructive. Detonations can be an immediate phenomenon, or can result hours after the release of a flammable gas when the chemical disperses to a concentration between its upper and LFLs and encounters an ignition source. The effects of overpressures on the CW, MOI and the public from either a delayed ignition detonation or immediate detonation are a function of its overpressure magnitude, the distance from the detonation (i.e., attenuation), and other mitigating factors (e.g., shielding from buildings).

ALOHA Version 5.4.4 and other peer-reviewed techniques and codes are required to determine the overpressures from a delayed ignition detonation, an immediate detonation, or a BLEVE. This version of ALOHA is in the DOE Central Registry and is capable of addressing the energetic events discussed in this subsection. It has the capacity to calculate toxic chemical consequences from pool fires, BLEVEs, flash fires or vapor cloud explosions, and jet fires.

ALOHA Version 5.4.4 only models combustion reactions and estimates the blast wave from unconfined vapor cloud explosions (e.g., fast deflagrations, detonations). Confined vapor cloud explosions generally produce more damaging blast waves than unconfined or partially confined explosions.

The overpressure calculation utilizes the Baker-Strehlow-Tang (BST) model (Pierorazio et al. 2005), employing non-dimensional, empirically-derived blast curves to establish overpressure. Overpressure magnitude is a function of the flame front propagation speed and the mass of fuel involved in the reaction.

ALOHA Version 5.4.4 models flame hazards associated with the combustion of liquids and gases. However, fire scenarios involving chemicals with flashpoints exceeding 300°F cannot be modeled. Two

types of combustion are addressed in ALOHA: (1) a fuel mixed with air to form a cloud with concentrations within the flammability range; and, (2) an overly-rich core of fuel that burns at its outer edges. Different methodologies are applied for estimating the threat zones for these two types of combustion events. ALOHA Version 5.4.4 employs solid flame models to compute thermal radiation hazards from fireballs, jet fires, and pool fires, where the flux of thermal radiation emitted from the surface of the flame is computed and the radiation impinging upon a distant target is determined.

ALOHA Version 5.4.4 has a BLEVE-fireball model based on studies of fireballs resulting from BLEVEs (American Institute of Chemical Engineers 1994). A fire thermally stresses a vessel causing the internal pressure to rise beyond the capacity of pressure relief valves, leading to a tank explosion. The tank contents are rapidly released and quickly flash boil as they depressurize, and both liquid droplets and gas ignite. Since the substance is too rich to burn; a fire burns at the surface where sufficient air can mix with the fuel resulting in a fireball that burns for tens of seconds. The flux of thermal radiation emitted from the burning surface is computed, and the radiation impinging upon a distant target is determined.

Example scenarios for pool fires (Example 1 Part 2), BLEVEs (Example 2 Part 1), flash fires or vapor cloud explosions (Example 2 Part 2), and jet fires (Example 2 Part 3) are provided in ALOHA Example Scenarios.

If a small quantity of chemical is spilled or released in a fire or explosion, the resultant plume can be approximated with the Gaussian plume model, as long as the additional plume buoyancy and explosion overpressures are addressed in other codes. EPIcode has an explosion sub-model that addresses this type of release, calculating a virtual point of release in three-dimensional space before applying Gaussian modeling techniques.

Other complicating factors, such as chemical reactions and chemical transformations within the plume, should be addressed on a case-by-case basis using the dispersion modeling protocol in Section 6.1.9. See Chapter 4 for additional information on energetic release phenomenology, chemical reactions and chemical transformations.

7.6 METEOROLOGICAL PARAMETERS AFFECTING TOXIC CHEMICAL CONSEQUENCE ANALYSIS

The discussion in the similar section in Section 6 on the meteorological parameters of wind speed, wind direction, sigma theta, temperature and precipitation are also applicable to toxic chemical releases. For these meteorological variables, the atmosphere does not operate any differently whether the release is a radionuclide or toxic chemical, or a combination of both. Turbulence typing for chemical dispersion and consequence analysis is the same as for radiological releases that was also described in Section 6. In calculating plume concentrations, both “typical” and “unfavorable” dispersion conditions are of special interest in accident analyses. The information described in Section 6 for radionuclides is also applicable to chemicals.

However, there are meteorological variables which are only meaningful to toxic chemical consequence analysis. These are:

- Temperature effects; and,
- Relative humidity effects.

7.6.1 TEMPERATURE EFFECTS

The atmospheric variables of temperature and moisture (e.g., relative humidity, absolute humidity, dew point temperature, wet-bulb temperature) do not directly affect the magnitudes of the atmospheric dilution and diffusion for radionuclide release evaluations. However, for releases of toxic chemicals, these variables play a significant role in determining the thermodynamics in establishing rates of flashing, aerosolization, and puddle evaporation.

Appendix G provides a discussion of puddle evaporation algorithms and heat balance including conduction from the ground surface. It also provides a discussion of impoundment basins and how they limit the surface area of the puddle and therefore reduce evaporation rate.

7.6.2 RELATIVE HUMIDITY EFFECTS

Uranyl hexafluoride (UF_6) is a special case due to its disassociation into hydrofluoric acid (HF) and uranyl fluoride (UO_2F_2) in a humid environment. A special code developed by Hanna in the 1980s, HGSYSTEM-UF6, and a recent version of the NRC code, RASCAL, has an algorithm to model the conversion rate of UF_6 to UO_2F_2 and HF over time and subsequently disperses both compounds.

Some chemical releases are also sensitive to ambient relative humidity; especially chemicals that are deliquescent and absorb water. An interesting situation is the release of ammonia (NH_3) in a dry environment, where it remains as a positively buoyant gas; while in a humid environment it becomes ammonium hydroxide (NH_4OH), which behaves as a dense gas.

The release of elemental tritium is also very sensitive to the amount of water vapor in the atmosphere at the time of release as it will convert to tritium oxide rapidly in a moist environment. There are significant differences in the DCFs between elemental tritium and tritium oxide.

7.7 TOXIC CHEMICAL ATMOSPHERIC TRANSPORT AND DIFFUSION MODELS

Many codes are available for evaluating toxic chemical releases, atmospheric dispersion, and concomitant consequences to the CW, MOI and the public. It has been estimated that in the 1980s, there have been as many as 250 atmospheric dispersion modeling codes available both internationally and within the private and public sectors of the United States. However, codes need to be maintained and improved in order to remain viable, so this number has decreased with time.

In 1995, the Subcommittee on Consequence Assessment and Protective Actions (SCAPA) published "*Atmospheric Transport Modeling Resources*" (Mazzola, 1995), in which information about various aspects of 94 distinct atmospheric transport models were catalogued and presented in an easy-to-use format. In March 1999, the Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM) published a much more comprehensive version of this document for 64 frequently used atmospheric dispersion models. This latter work is available electronically by accessing the OFCM web page (www.ofcm.gov). In addition, the Accident Phenomenology and Consequence (APAC) Methodology Evaluation Program analyzed 15 radiological dispersion models (Working Group 5) (APAC5, 2002) and 25 chemical dispersion models (Working Group 6) (APAC6 1997) in significant detail.

Some models have undergone extensive SQA inclusive of verification and validation. Other codes are available and may be more appropriate for some applications but were not included in those summaries because they are not commonly accessible or require specialized knowledge for their proper use.

7.7.1 NEUTRALLY-BUOYANT GAUSSIAN MODELS

Gaussian models, due to their relative simplicity and ease of application, are the most common atmospheric dispersion models employed by analysts to determine consequences from toxic chemical releases. There are two chemical dispersion models (i.e., ALOHA, EPIcode) in the DOE CR, ALOHA meets all DOE O 414.1D and DOE G 414.1-4 SQA guidance and although EPIcode does not, it is still determined to be adequate for safey analysis

- Areal Locations of Hazardous Atmospheres (ALOHA) Version 5.4.4, an EPA and National Oceanic and Atmospheric Administration (NOAA)-sponsored code (Ref. 19); and,
- Emergency Prediction Information code (EPIcode), Version 7.0 (Ref. 20).

ALOHA is the more versatile of the two toolbox codes as it contains both dense-gas and neutrally-buoyant dispersion models, and it can address various energetic events. During an ALOHA neutrally-buoyant dispersion model execution, the code selects one model based on the environment in which the release is occurring, the nature of the release, the toxic chemical being analyzed and the source-receptor distance of interest. For dense gas releases, ALOHA calculates the dispersion within the dense gas "blanket" and with each succeeding time step, evaluates whether the plume, which is gradually entraining ambient neutrally-buoyant air, still will disperse as a dense gas. Once the plume parameters no longer support the definition of a dense gas as it moves further downwind, ALOHA switches to the neutrally-buoyant Gaussian model. In contrast, EPIcode is based only on the neutrally-buoyant atmospheric dispersion model, but allows the user to vary the release time and deposition velocity, as well as implement a building wake effect model.

7.7.1.1 ALOHA

The ALOHA code was jointly developed by EPA and the hazardous materials division of NOAA. It is part of the Computer-Aided Management of Emergency Operations (CAMEO) suite of codes and is used primarily for emergency response situations and for training. As such, it is user-friendly, allowing easy data input and convenient output of areal maps with contours of concentration of toxic chemicals using the MARPLOT feature. Many of the internal features of the code are hidden from the user in order to make it more user-friendly. The full suite of ALOHA modeling capabilities can be referenced in NOAA Technical Memorandum NOS OR&R 43, ALOHA technical documentation (Reference).

Unlike some radiological dispersion codes (e.g., MACCS2, GENII, Hotspot), ALOHA does not have the capability to incorporate hourly, site-specific meteorological data and calculate 95th percentile levels consequences based on meteorological variability. EPIcode Version 7.0 has been recently upgraded to execute with hourly meteorological data files. For ALOHA applications, a single combination of atmospheric stability and wind speed is input instead of hourly meteorological data files. For dispersion analysis appropriate to DOE-STD-1189-2008 Appendix B, 40 CFR 68.22(b) specifies that poor dilution and diffusion conditions of 1.5 m/sec wind speed and F atmospheric stability class should be assumed.[39]

[39] **Wind speed and atmospheric stability class**. "For the worst-case release analysis, the owner or operator shall use a wind speed of 1.5 m per second and F atmospheric stability class. If the owner or operator can demonstrate that local meteorological data applicable to the stationary source show a higher minimum wind speed or less stable atmosphere at all times during the previous three years, these minimums may be used. For analysis of alternative scenarios, the owner or operator may use the typical meteorological conditions for the stationary source" (40 CFR 68.22(b)).

Related conditions of ambient temperature and relative humidity, as may be needed, are recommended from the prescription also identified in 40 CFR 68.22(b).[40]

ALOHA is intended for the evaluations of the consequences of toxic chemical releases. If the chemical released is a heavy gas, a heavy-gas model (i.e., a stripped down version of DEGADIS) is used; otherwise, a neutrally-buoyant Gaussian model is used. ALOHA computations represent a compromise between accuracy and speed: it has been designed to produce good results quickly enough to be of use to first responders.

ALOHA Version 5.4.4 has the following attributes:

- Since evaporation of volatile chemicals is especially time-variant, ALOHA can calculate the time-dependent Qevaporation source term and resulting plume concentration;
- It can determine the extent of dense gas behavior and the distance of transition to neutrally buoyant gas behavior;
- It can predict the rates at which chemical vapors may escape into the atmosphere from broken gas pipes, leaking tanks, and evaporating puddles;
- It can address energetic events such as BLEVEs, vapor cloud explosions, detonations, delayed ignition detonations, and radiant heat effects of flash fires and jet fires;
- Its chemical library contains information about the physical properties of about 3,000 common toxic chemicals;
- It has a Site Acquisition of Meteorology (SAM) option, where an instrumented meteorological tower can provide input directly to the code; and,
- It permits changes in the wind direction parameter every fifteen minutes when the SAM component is applied. When used in this mode, changes in wind direction allow the plume to bend in the downwind direction. This is known as the segmented Gaussian plume.

ALOHA Version 5.4.4 has the following limitations:

- It does not calculate plume rise for ground level releases, so it cannot realistically account for the enormous buoyancy effects of fires;
- It only addresses pure chemicals and consequently is not capable of analyzing the complexities of atmospheric chemistry associated with chemical reactions and mixtures of chemicals;
- It does not have any algorithms that account for dry deposition, wet deposition, plume depletion, and resuspension. Therefore it does not do particularly well for releases that contain particulates;
- It is a straight-line, or at best, a segmented plume Gaussian model, which limits its ability to address complex flows associated with topography; and,
- Like all Gaussian models that are steady-state by definition, is not reliable for very low wind speeds, for very stable atmospheric conditions, for shifting winds and terrain-steering situations, or for concentration patchiness.

[40] **Ambient temperature and relative humidity**. "For worst-case release analysis of a regulated toxic substance, the owner or operator shall use the highest daily maximum temperature in the previous 3 years and average humidity for the site, based on temperature/humidity data gathered at the stationary source or at a local meteorological station; an owner or operator using the Risk Management Program (RMP) Offsite Consequence Analysis Guidance may use 25 °C and 50 percent humidity as values for these variables. For analysis of alternative scenarios, the owner or operator may use typical temperature/humidity data gathered at the stationary source or at a local meteorological station" (40 CF. §68.22(c)).

7.7.1.2 EPICODE

The Emergency Prediction Information (EPI) code was originally developed at the Lawrence Livermore National Laboratory (LLNL). It was developed to provide emergency response personnel and emergency planners with a software tool to help evaluate downwind concentrations from atmospheric releases of toxic substances. It can also be used for safety analysis planning purposes on facilities handling toxic chemicals.

EPIcode has many similarities to ALOHA, in that it is a straight-line Gaussian model with an extensive chemical library. However, unlike ALOHA, it can only address direct and puddle chemical release situations since it does not contain pipe and tank sub-models.

EPIcode Version 7.0 has the following attributes:

- It can assess area releases, fire releases, and explosion releases; but not the energetics associated with these accidents;
- Its chemical library is slightly smaller than that in ALOHA, but it still addresses more than 600 specific chemicals;
- It has algorithms for dry deposition;
- It allows fast estimation and assessment of chemical release scenarios associated with accidents from industry and transportation;
- It is menu-driven and user friendly, requiring minimal user training. It contains a good graphics package; and
- Its User Manual also contains 11 case studies showing how the code can assess a wide range of chemical accident scenarios.

EPIcode Version 7.0 has the following limitations:

- It has a very simple evaporation rate algorithm.
- It only addresses pure chemicals and consequently is not capable of analyzing the complexities of atmospheric chemistry associated with chemical reactions and mixtures of chemicals;
- It does not have any algorithms that account for wet deposition and resuspension;
- It is a straight-line Gaussian model, which limits its ability to address complex flows associated with topography; and,
- Like all Gaussian models that are steady-state by definition, is not reliable for very low wind speeds, for very stable atmospheric conditions, for shifting winds and terrain-steering situations or for concentration patchiness.

7.7.1.3 CHEMICAL DISPERSION ANALYSIS WITH ALOHA AND EPICODE

A limited parametric study provides insight to important sensitivities related to modeling evaporative of chemicals with an earlier version of ALOHA and analysis of the concentrations at 100-m (Thoman, 2006). This study, summarized in Table 7-4, yielded the following conclusions:

- F stability condition at 1 m/s wind speed for a rural region of transport is bounding relative to urban conditions for both EPIcode and ALOHA. The same conclusion holds for the results comparing the D stability and 2 m/s results; and,
- ALOHA dense gas results for D stability and 2 m/s wind speed bounds the Gaussian neutrally-buoyant gas results for both rural and urban regions of transport, and the rural terrain dense gas results for D stability and 2 m/s wind speed are bounding relative to the urban terrain dense gas results.

Table 7-4. ALOHA Results for Evaporative Releases of Four Selected Chemicals.

Chemical Released	Dispersion Model[41]	Region of Transport	Stability class/ wind speed (m/s)	Release rate (g/s)	Concentration at 100 m (mg/m^3)
Nitric Acid	GM	Rural	F/1	5.3	2.3 E2
	DG	Rural	F/1	5.3	8.8 E1
	GM	Urban	F/1	5.3	4.8 E1
	DG	Urban	F/1	5.3	6.1 E1
Nitric Acid	GM	Rural	D/2	9.1	3.2 E1
	DG	Rural	D/2	9.1	7.3 E1
	GM	Urban	D/2	9.1	1.3 E1
	DG	Urban	D/2	9.1	4.9 E1
Chlorine	GM	Rural	F/1	2100	2.1 E4
	DG	Rural	F/1	2100	3.0 E3
	GM	Urban	F/1	2100	4.4 E3
	DG	Urban	F/1	2100	1.5 E3
Chlorine	GM	Rural	D/2	2800	2.4 E3
	DG	Rural	D/2	2800	2.6 E3
	GM	Urban	D/2	2800	9.5 E2
	DG	Urban	D/2	2800	1.6 E3
Benzene	GM	Rural	F/1	9.6	4.3 E2
	DG	Rural	F/1	9.6	1.3 E2
	GM	Urban	F/1	9.6	9.0 E1
	DG	Urban	F/1	9.6	9.1 E1
Benzene	GM	Rural	D/2	17	4.9 E1
	DG	Rural	D/2	17	1.1 E2
	GM	Urban	D/2	17	2.0 E1
	DG	Urban	D/2	17	7.4 E1
Ammonia	GM	Rural	F/1	400	6.9 E3
	DG	Rural	F/1	400	7.6 E2
	GM	Urban	F/1	400	1.4 E3
	DG	Urban	F/1	400	6.7 E2
Ammonia	GM	Rural	D/2	540	8.6 E2
	DG	Rural	D/2	540	1.3 E3
	GM	Urban	D/2	540	3.5 E2
	DG	Urban	D/2	540	8.7 E2

[41] GM=Gaussian neutrally-buoyant; DG = Dense Gas or heavy gas

For the same chemical release under evaporative conditions, the neutrally-buoyant Gaussian model ALOHA results for the F stability conditions and 1 m/s wind speed for a rural region of transport bounds all other dense gas results in both rural and urban regions of transport and all other neutrally-buoyant Gaussian model results. For example, the neutrally-buoyant nitric acid result of 230 mg/m^3 for F stability and 1 m/s wind speed bounds the other seven chlorine results obtained using the ALOHA model. Chemical release concentrations for the three other toxic chemicals also showed the same bounding value for F stability conditions and 1 m/s wind speed for a rural region of transport.

Both EPIcode and ALOHA allow the evaporative source term and dispersion calculations to be coupled such that the plume exposure time reflects the time over which the evaporation release occurs. For EPIcode, an evaporation rate that is constant with time is modeled. ALOHA calculates a time–varying evaporative release rate that is reflected in downwind concentrations that are observed vary with time as shown in Figure 7.7-1.

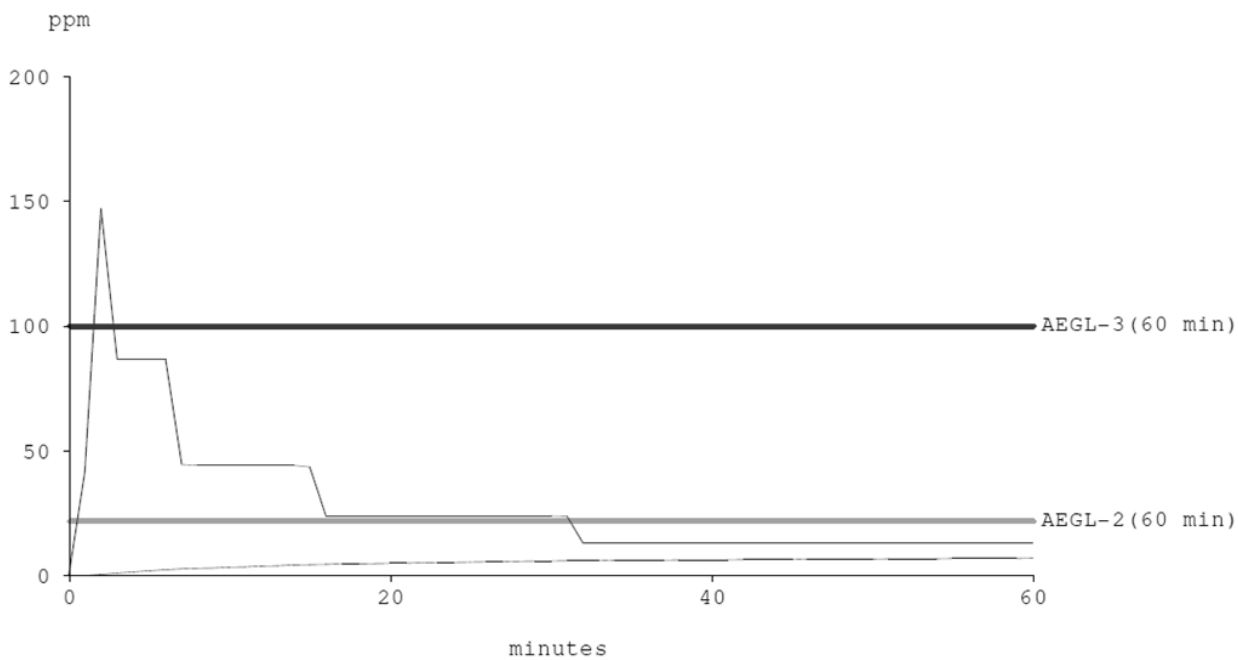


Figure 7-1. Example of ALOHA concentration output from an evaporative pool of hydrogen chloride.

7.7.2 DENSE GAS DISPERSION MODELS

Practically all of the hazardous chemicals that are stored and/or used at DOE facilities have densities greater than dry air. Some exceptions include anhydrous ammonia, nitric oxide and carbon monoxide.

Several heavy gas or dense gas codes have been developed to analyze the slumping effects of an accidental release of a dense gas. Each of these codes has been recommended for application in a broad range of Safety Basis Documentation by APAC Working Group 6.

7.7.2.1 ALOHA

ALOHA can also be executed in heavy gas mode, if not bypassed by the user, for a release of a chemical with a molecular weight of greater than the molecular weight of dry air (28.97 g/mol) given that the critical Bulk Richardson number criterion is fulfilled during release conditions. ALOHA contains a stripped down version of the DEGADIS code to address the effects of heavy gases.

ALOHA can be run in normal Gaussian mode or dense gas mode. For dense gas applications, the dense gas model operates until the critical Bulk Richardson number is reached as the dense gas plume gradually entrains ambient air into the blanket. Once sufficient ambient air is within the dense gas blanket, ALOHA switches to the Gaussian model.

NSRD-2015-TD01, Technical Report for Calculations of Atmospheric Dispersion at Onsite Locations for Department of Energy Nuclear Facilities, concluded:

> *"The ALOHA model indicates that the enhanced horizontal dispersion resulting from the dense gas itself on the ambient atmosphere is more than sufficient to overcome the reduced vertical dispersion associated with the dense gas response to gravity; therefore, the neutrally buoyant case is sufficiently bounding."*

7.7.2.2 DEGADIS

Version 1 of the DEnse GAs DISpersion model was developed by the University of Arkansas for the United States Coast Guard (USCG) and the Gas Research Institute (GRI) in 1985. In 1988, Havens (1988) interfaced Ooms' 1974 jet model to develop Version 2.0. The present Version 2.1 was established in 1989 through the work of Spicer and Havens.

EPA lists DEGADIS as an "Appendix B" refined air quality model that may be considered for individual regulatory applications on a case-by-case basis. It presently manages the maintenance of the model. Updates on can be accessed through the EPA SCRAM bulletin board http://www.epa.gov/scram001/tt22.htm#degadis).

Although the model is relatively easy to run, the analyst should take special care to fully understand the user options and the data input requirements (e.g., distinctions between isothermal and non-isothermal simulations).

DEGADIS has the following attributes:

- It can address the transport and diffusion of many types of dense gas releases and account for a variety of surface roughness elements; and,
- It can also simulate atmospheric transport and diffusion of pure chemical releases in passive-dispersion flow regimes.

DEGADIS has the following limitations:

- It does not have a front-end chemical library that the ALOHA and EPIcode models have. Correspondingly, the analyst needs to couple the DEGADIS dispersion results with chemical source terms generated from other models; and,
- It cannot address buoyant plumes, although it is usually chosen for application for cases where the plume slumps due to its own density.

7.7.2.3 HGSYSTEM

Heavy Gas (HG) SYSTEM was developed for the American Petroleum Institute (API) in 1990. Its current version, 3.0, was released in 1994.

Unlike DEGADIS and SLAB, HGSYSTEM is able to generate its own chemical source terms and therefore does not need to be supplied with an additional modeling technique.

HGSYSTEM has the following attributes:

- It can efficiently handle time-dependent dispersion by an internal automated selection of advection and averaging time; and,
- It can also treat multi-component mixtures and vapor-aerosol generation.

HGSYSTEM has the following limitations:

- Proper training is needed. Although not as complex as a research-grade model, the user needs prior experience and familiarity with the code's features since there are a large number of alternative options available that need to be fully understood; and,
- It also has had difficulty in appropriately quantifying evaporation under low exit velocity release conditions and very stable low wind speed meteorological conditions.

A specially designed HGSYSTEM-UF_6 model has been developed for use in the accident analysis of Oak Ridge facilities to quantify the chemical consequences from a release of uranium hexafluoride.

7.7.2.4 SLAB

SLAB was developed from basic research involving experiments with chemical releases at China Lake, CA and the Nevada Test Site (NTS) in the early 1980s (Ermak, 1995).

SLAB has the following attributes:

- It is not only easy to use, but it can be applied to a wide range of chemical release scenarios. These include application to jets released at any angle to evaporative area sources to instantaneous sources.; and,
- It also contains a unique averaging time algorithm that allows application of the model to time varying source emissions.

SLAB has the following limitations:

- Like DEGADIS, it does not have a front-end chemical library that the ALOHA and EPIcode models have;
- The analyst needs to couple the SLAB transport and diffusion results with chemical source terms generated from other models; and,
- SLAB cannot address buoyant plumes.

7.7.3 VARIABLE TRAJECTORY DISPERSION MODELS

The frame of reference of all steady-state two-dimensional Gaussian-type models is Eulerian, meaning that the receptor is on a fixed coordinate system and receives no impact until the plume front reaches it. For sites that are located in regions that experience three-dimensional flows due to complex terrain (i.e., valley-mountain wind regimes) or due to temperature differences at land-water interfaces (i.e., sea breezes, lake breezes), the application domain of Eulerian codes is severely limited.

For the evaluation of chemical releases at locations with complex air flows, three-dimensional Lagrangian mass-consistent codes, [e.g., National Atmospheric Release Advisory Center (NARAC)] need to be considered for toxic chemical releases. However, since the distance to the CW is sufficiently close enough where airflow trajectory reversals have not yet begun to occur, there is no practical need to be concerned with these complex terrain effects for this application.

Several models have been developed to characterize atmospheric dispersion in regions of complex terrain. The following presents a few of these models that can be applied to address the effects of chemical as well as radiological releases in mountain-valley and sea breeze topographic settings. These include:

- NARAC;
- HYSPLIT;
- HYRAD;
- AERMOD; and
- CTDMPLUS.

7.7.4 RESEARCH-GRADE DISPERSION MODELS

Several research grade atmospheric transport and dispersion models are applicable to chemical consequence analysis. The APAC Working Groups reviewed several of these codes, which include:

- HOTMAC/RAPTAD;
- FEM3C;
- SCIPUFF;
- VDI; and
- VLSTRACK.

The analyst is referred to the APAC Working Group 6 report for further information regarding the applicability of any of these codes to specific problem solving.

7.8 TOXIC CHEMICAL CONSEQUENCE SCOPING METHODOLOGY TO EXCEED PAC VALUES

As discussed in Section 2.4.5, Chemical Hazard Evaluation, and Section 7.3, Chemical Screening Criteria, chemical hazards are screened for further hazard evaluation by applying criteria such as in Section A.2 of the DOE-STD-3009-2014. For some of those hazards that are not screened out, a qualitative evaluation of toxic chemical consequences is generally sufficient to provide a basis for comparison to the qualitative consequence thresholds in Table 2-8, Consequence Thresholds, of this Handbook. However, for some of those hazards that are not screened out, a quantitative evaluation may be necessary to determine impacts to CWs, the MOI and the public, when the toxic chemical hazards have the potential to exceed the SS control selection criteria.

This section provides a simplified quantitative scoping methodology for determination of toxic chemical quantities that are sufficient to challenge the screening criteria. This scoping methodology is based on the EPA-550-B-99-009, March 2009, *Risk Management Program Guidance for Offsite Consequence Analysis* (EPA 2009) for liquid evaporation, and from a 2007 calculation, SB-DO:CALC-07-024, "Chemical Threshold Quantities for Safety Basis Categorization", for gas, powder, and solid releases.

This scoping methodology is applied to the following toxic chemical releases:

- Gas, powder, and solid release (Section 7.8.1); and
- Evaporation of a liquid release (Section 7.8.2).

Section 7.8.3 compares the scoping methods to applicable PAC values for the MOI high consequence case.

7.8.1 GAS, POWDER, AND SOLID RELEASE MODEL

For all of the cases presented, the downwind toxic chemical concentration, C(x), in mg/m^3, can be described by the following equation:

$$C(x) = Q' \times \chi/Q(x) \qquad \textbf{Equation 7.8-1}$$

Where,

Q' = release rate (mg/s)
χ/Q (x) = atmospheric dispersion factor at receptor of interest distance (x) (s/m^3)

The distinction between powders and solids is based on how they are treated in the DOE-HDBK-3010-94, and Chapter 5 of this Handbook. For gas, powder, and solid releases, the model to calculate the release rate, (Q') of a toxic chemical (i.e., MAR) that will exceed applicable PAC values is calculated by the following equation:

$$Q' = ST / t \qquad \textbf{Equation 7.8-2}$$

Where,

ST = source term released to air (mg)
t = release duration (s)

Note: Assume 900 s for 15-min Time Weighted Average (TWA) for concentration dependent chemicals, as discussed in Section 7.2, Chemical Consequence Assessment Fundamentals. EPA assumes a10-min release duration for gaseous releases, which would result in the same 15-min TWA when accounting for 5-min with no release.

The five-factor ST formula from Equation 5-1 can be reduced to ST = MAR × ARF based on a conservative assumption for the unmitigated analysis that all of the MAR is released or spilled (1.0 DR), all released MAR is of respirable size (1.0 RF)[42], and all airborne release within a facility is released to the environment (1.0 LPF)[43]. Combining this conservative ST equation with Equations 7.8-1 and 7.8-2,

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[42] EPA-550-B-99-009 allows <100 μm fraction with 1.0 ARF for powders released over 10 min. However, this is not used in this screening calculation

[43] EPA-550-B-99-009 allows a LPF = 0.55 for in-facility deposition However, this is not used in this screening

the MAR quantity released or spilled is presented as a function of the concentration, release duration, ARF, and atmospheric dispersion factor in Eq. 7.8-3:

$$MAR = [C(x) \times t] / [ARF \times \chi/Q(x)] \qquad \textbf{Equation 7.8-3}$$

For this scoping calculation, conservative facility-wide estimates of ARF based on a similar logic applied for nuclear hazard categorization determinations per DOE-STD-1027-92, Chg. Notice 1, as used in the referenced calculation, are as follows:

ARF = 1.0 for a gas
ARF = 0.01 for a powder
ARF = 0.001 for a solid[44]

7.8.2 LIQUID EVAPORATION SCOPING MODEL

For sub-cooled liquids, where no heated correction factor is required, the evaporation model used to calculate the release rate, Q', is from EPA-550-B-99-009 Equation D-1 (see the EPA reference for its derivation and English to metric unit conversions that are reflected in the constants in the Equation 7.8-4), which is based on surface area and volume of the spill, density, vapor pressure, and molecular weight of the liquid; and wind speed; as shown in Eq. 7.8-4:

$$Q' = [0.284 \times u^{0.78} \times MW^{2/3} \times A \times VP]/[82.05 \times T] \qquad \textbf{Equation 7.8-4}$$

Where,

Q' = release rate (lb/min)
U = wind speed (m/s)

Note: Assume U = 1.0 m/s, F Stability to be consistent with 95th percentile χ/Q.

MW = molecular weight
A = V/h = unconfined surface area of pool (1 cm depth per EPA-550-B-99-009, converted to ft)
h = dike height for confined pool (ft)
V = MAR/ρ = volume of liquid spilled (ft^3)
ρ = density of liquid = specific gravity × 1.0 g/cm^3
VP = vapor pressure at ambient temperature (mm Hg)

$$VP = [VP_{data} / T_{data}] \times 298°K\ [25°C] \qquad \textbf{Equation 7.8-5}$$

T = liquid temperature (°K)

Equation 7.8-5 is based on the method from calculation SB-DO:CALC-07-024 that adjusts the VP for temperatures other than 25°C[45] by the Ideal Gas Law (i.e., according to the linear function from zero at 0 Kelvin to the tabulated vapor pressure and temperature from a chemical reference). VP is the most sensitive parameter for application of Equation 7.8-4, and can be obtained from the PAC website for pure

calculation.

[44] EPA-550-B-99-009 evaluates powder in solution, or solids in molten form, with different methods

[45] That calculation was based on 20°C, which has been revised to 25°C per the EPA methodology used for this scoping calculation.

chemicals, or for lesser concentrations, can be obtained from chemical references such as Perry's Chemical Engineer's Handbook (Reference). As an alternate method to Equation 7.8-5, Figure 7-2 illustrates how the vapor pressure varies as a function of the liquid temperature for a 70 wt% nitric acid water solution. The vapor pressure data are from Table 3-16 of *Perry's Chemical Engineer's Handbook (Fourth Edition)*, and from EPIcode predictions (DAC-F000Y12-F-0004 000 00).

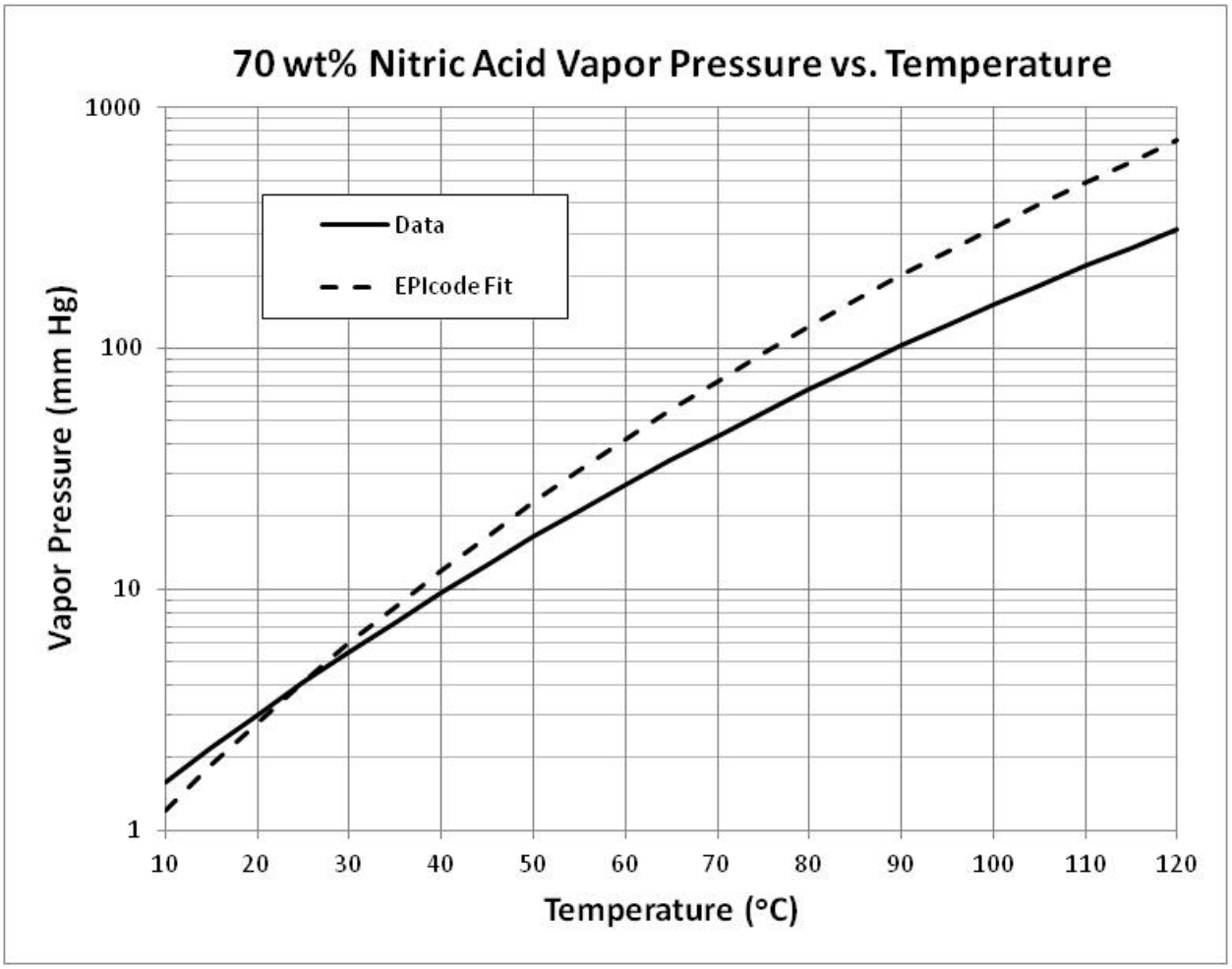

Figure 7-2. Comparison of Vapor Pressure Data vs. EPIcode Fit for 70 wt% Nitric Acid.

A recommended release rate correction factor (CF) to account for liquids with high VP at ambient T of 298°K (25°C) is shown in Eq. 7.8-6.

$$CF = - [P_a / VP] \times [\ln (1 - VP/P_a)] \qquad \textbf{Equation 7.8-6}$$

Where,

P_a = 760 mm Hg ambient pressure @ Standard Temperature and Pressure, or local ambient P_a

For liquids with high vapor pressures, the corrected release rate (mg/s) becomes:

$$Q''/A = CF \times [0.284 \times u^{0.78} \times MW^{2/3} \times VP]/[82.05 \times T] \qquad \textbf{Equation 7.8-7}$$

The spill temperature, *T*, should be selected considering the range of possible liquid temperatures, consistent with the storage/operating temperature or the temperature of the environment. For normal spills of liquids, not resulting from fire events, if conditions differ significantly from the default 25°C from EPA-550-B-99-009, the spill temperature should be selected as the greater of: (1) the maximum storage/operating temperature; or, (2) the 95th percentile ambient temperature for conservative dispersion conditions consistent with the χ/Q calculation.

For spills of liquids under fire conditions where the fire is of sufficient size to cause bulk boiling of the spilled liquid, the spill temperature should be selected as the normal boiling point of the spilled material. Otherwise, the spill temperature should be selected as the greater of: (1) the maximum storage/operating temperature; or, (2) the 95th percentile ambient temperature for conservative dispersion conditions consistent with the χ/Q calculation. Other corrections (i.e., VP, density) are also required as recommended in EPA-550-B-99-009.

The time to evaporate the entire MAR spilled or released, t_{evap}, is:

$$t_{evap} = [\rho \times h]/[Q''/A] \qquad \textbf{Equation 7.8-8}$$

Using the above equations, the quantity of toxic chemical MAR to exceed a specified concentration for high-vapor pressure liquids, at a downwind distance (x) can be calculated using Eq. 7.8-9:

$$MAR = [C(x) \times \rho \times h]/[Q''/A \times \chi/Q(x)] \times [900/\text{minimum}\ (t_{evap}, 900)] \qquad \textbf{Equation 7.8-9}$$

The 900 primarily refers to a concentration-dependent chemical. Note that the last term of Equation 7.8-9 adjusts for rapid $t_{evap} < 900$ s, or makes no adjustment for slow evaporation > 900 s. Thus, for evaporation that takes place over a >900 sec period, the last term is unity.

Lastly, the t_{evap} term can be modified by multiplying by % weight fraction of chemical concentration for liquids with impurities using Raoult's Law.

7.8.3 SCREENING METHOD FOR MAXIMALLY-EXPOSED OFFSITE INDIVIDUAL (MOI) HIGH CONSEQUENCE

Since the release is ground-level the MOI will be at the site boundary. For the MOI, the relevant inputs to Equations 7.8-3 and 7.8-9 are:

C (site boundary) =PAC-2 (PAC, 2012)

χ/Q (site boundary) = dispersion factor at site boundary for MOI (s/m^3)

The MOI MAR quantity of toxic chemical to exceed PAC-2 is determined for high VP liquid releases and other releases in Equations 7.8-10 and 7.8-11, respectively.

High VP liquid releases:

$$MAR = [PAC\text{-}2 \times \rho \times h]/[Q''/A \times \chi/Q\ (\text{site boundary})] \times [900 / \text{minimum}(t_{evap}, 900)] \qquad \textbf{Equation 7.8-10}$$

Other releases:

$$MAR = [PAC\text{-}2 \times t]/[ARF \times \chi/Q(\text{site boundary})] \qquad \textbf{Equation 7.8-11}$$

To estimate the MAR that could exceed the MOI moderate consequence threshold, the high consequence MAR can be multiplied by the PAC-1/PAC-2 ratio, or alternately, can be scaled by the moderate CW consequence MAR by χ/Q (100 m)/χ/Q(site boundary) ratio.

The site-specific overall 95th percentile sector independent χ/Q or 99.5th percentile sector dependent χ/Q as determined by Section 6.1.10, DOE-STD-3009-2014 Atmospheric Dispersion Options, is applicable. Alternately, the following conservative assumptions can be made using the Tadmor-Gur rural dispersion factors for F Stability and wind speed (U) of 1 m/s, with a 3 cm surface roughness factor assumed in the modeling protocol. Note that this is the same as the reference value from the original experiments.

For illustration purposes, a minimum distance to the site boundary of 1 km is used in the following equations and in Section 7.9.

$$\sigma_z(x) = 0.2 \times x^{0.602} \times (\text{surface roughness}/3\text{ cm})^{0.2} = 12.79 \text{ m at 1 km} \quad \textbf{Equation 7.8-12}$$

$$\sigma_y(x) = 0.0722 \times x^{0.9031} = 36.97 \text{ m at 1 km} \quad \textbf{Equation 7.8-13}$$

$$\chi/Q\,(x) = [\pi \times u \times \sigma_y(x) \times \sigma_z(x)]^{-1} = 6.73\text{ E-4 s/m}^3 \text{ at 1 km} \quad \textbf{Equation 7.8-14}$$

7.9 EXAMPLE TOXIC CHEMICAL CALCULATIONS

Four example calculations, representing a range of plausible release types and liquid release vapor pressures, are provided in the following subsections:

- Gas (ammonia);
- Powder (aluminum oxide);
- Liquid evaporation of an unconfined spill (70% nitric acid); and,
- Liquid evaporation of a confined spill into a diked area (55% hydrofluoric acid).

These calculations are all based on the CW method, exceeding the PAC-3 threshold. As previously indicated, these results can be scaled to estimate the quantity to exceed PAC-2 moderate consequence for the CW or to exceed the MOI high PAC-2 threshold or moderate PAC-1 threshold.

7.9.1 EXAMPLE 1: CALCULATE AMMONIA GAS QUANTITY THAT EXCEEDS PAC-3 AT THE CW

Eq.7.8-11, modified for the CW χ/Q (100m) = 3.5E-3 s/m^3, applies to this example with the following inputs and assumptions:

C (100 m) = PAC-3 at 100 m = 770 mg/m^3 [PAC, 2012] for ammonia CASRN 7664-41-7
t = 900 s [15 min TWA]
ARF = 1.0 for gaseous release
χ/Q (100m) = 3.5E-3 s/m^3

MAR = [PAC-3 × t]/[ARF × 3.5 E-3 s/m^3]
MAR (100 m) = [(770 mg/m^3)(900 s)] / [(1.0)(3.5E-3 s/m^3)] × [lb/453.6 g × g/1,000 mg]

Conclusion: MAR = 4.37 E+2 lb or greater of ammonia gas, needs to be released to exceed PAC-3 at the CW.

7.9.2 EXAMPLE 2: CALCULATE ALUMINUM OXIDE QUANTITY THAT EXCEEDS PAC-3 AT THE CW

Eq.7.8-11, modified for the CW χ/Q (100m) = 3.5E-3 s/m^3, applies to this example with the following inputs and assumptions:

C (100 m) = PAC-3 at 100 m = 25 mg/m^3 [PAC, 2012] for aluminum oxide, CASRN 1344-28-1

t = 900 s [15 min TWA]
ARF = 0.01 for powder release
χ/Q (100m) = 3.5E-3 s/m^3

MAR = [PAC-3 × t]/[ARF × 3.5 E-3 s/m^3]
MAR (100 m) = [(25 mg/m^3)(900 s)] / [(0.01)(3.5E-3 s/m^3)] × [lb/453.6 g × g/1,000 mg]

Conclusion: MAR = 1.42 E+3 lb or greater of aluminum oxide, needs to be spilled to exceed PAC-3 at the CW.

7.9.3 EXAMPLE 3: CALCULATE LIQUID 70% NITRIC ACID QUANTITY THAT EXCEEDS PAC VALUES AT 1 KM SITE BOUNDARY

Eq.7.8-10, modified for the CW χ/Q (100m) = 3.5E-3 s/m^3, applies to this example with the following inputs and assumptions: 70% nitric acid is a high vapor pressure release, and spill occurs at sea level under Standard Temperature and Pressure (STP) conditions. Note that ARF is not applicable to a liquid evaporation release, and the duration (t) is the evaporation time if less than the 15-min as used for the TWA calculation. References for the input data are included in [brackets].

PAC-3 = 91.9 ppm = 237 mg/m^3 [2.58 mg/m^3/ppm from PAC, 2012] for nitric acid, CASRN 7697-37-2.

MW = 63.01 g/mol

VP = 4.49 mm Hg @ 26.4°C (299.4°K) [DAC-F000Y12-F-0004 000 00 for site-specific F Stability]

VP = [VP_{data} /T_{data}] × 298°K

VP = (4.49 mm Hg)/(299.4°K/298°K) = 4.47 mm Hg @ 25°C

SpG = 1.4134 @ 20°C [SB-DO:CALC-07-024]

ρ = 1.4134 g/cm^3

T = temperature of liquid = ambient 25°C = 298°K

P_a = 760 mm Hg @ ambient Standard Temperature and Pressure

h = 1.0 cm; depth of unconfined puddle [EPA-550-B-99-009]

u = 1.0 m/s; wind speed [consistent with χ/Q wind speed assumption for F Stability]

Q' = [0.284 × $u^{0.78}$ × $MW^{2/3}$ × A × VP]/[82.05 × T]

Q'/A = [0.284 × $u^{0.78}$ × $MW^{2/3}$ × VP]/[82.05 × T]

Q'/A = [0.284 × (1 m/s) $^{0.78}$ × $(63.01)^{2/3}$ × (4.47 mm Hg)]/[82.05 × 298°K] = 8.22E-4 lb/min/ft^2

CF = - [P_a /VP] × [ln (1 – VP/P_a)]

CF = - [(760 mm Hg)/(4.47 mm Hg)] × [ln (1 – (4.47 mm Hg)/(760 mm Hg)] = 1.003

Q''/A = CF × [0.284 × $u^{0.78}$ × $MW^{2/3}$ × VP]/[82.05 × T]

Q''/A = (1.003)(8.22E-4 lb/min/ft^2) = 8.24E-4 lb/min/ft^2

Q''/A = (8.24E-4 lb/min/ft^2)(453.6 g/lb)(min/60 s)(0.0328 ft/cm)^2 = 6.71E-6 g/s/cm^2

t_{evap} = [ρ × h]/[Q''/A]

t_{evap} = [(1.4134 g/cm^3) × (1.0 cm)]/[(6.71E-6 g/s/cm^2)] = 2.1 E+5 s (min/60 s) = 3.5 E+3 min > 15 min (no adjustment =1).

MAR = [PAC-3 × ρ × h]/[Q''/A × 3.5E-3 s/m^3] × [900/minimum (t_{evap}, 900)]

MAR = [(237 mg/m^3)(1.4134 g/cm^3)(1.0 cm)] / [(6.71E-6 g/s/cm^2) × (3.5E-3 s/m^3)] × [1] × (lb/453.6 g) × (g/1,000 mg)

Conclusion: MAR = 3.1E+4 lb or greater of 70% nitric acid needs to be spilled, to exceed PAC-3 at the CW.

For perspective a spill of 3.1E+4 lb of 70% nitric acid translates to:

Volume spilled = 2,666 gal

Puddle area = 81,271 ft^2

Puddle diameter = 322 ft

To exceed High MOI consequences at 1 km, Equation 7.8-12 applies with the following inputs:

PAC-2 = 62 mg/m^3 [PAC, 2012]

χ/Q (site boundary) = 6.73E-4 s/m^3

MAR = [PAC-2 × ρ × h]/[Q''/A × χ/Q (site boundary)] × [900/minimum (t_{evap}, 900)]

MAR = [(62 mg/m^3)(1.4134 g/cm^3)(1.0 cm)]/[(6.71E-6 g/s/cm^2)(6.73E-4 s/m^3)] × [1] × (lb/453.6 g) × (g/1,000 mg)

Conclusion: MAR = 4.28 E+4 lb or greater of 70% nitric acid needs to be spilled, to exceed PAC-2 at a site boundary distance.

7.9.4 EXAMPLE 4: CALCULATE LIQUID 55% HYDROFLUORIC ACID QUANTITY THAT EXCEEDS PAC VALUES AT 1 KM SITE BOUNDARY

Eq.7.8-10, modified for the CW χ/Q (100m) = 3.5E-3 s/m^3, applies to this example with the following inputs and assumptions: 55% hydrofluoric acid is a high vapor pressure release, and spill occurs at sea level under STP conditions. Note that ARF is not applicable to a liquid evaporation release, and the duration (t) is the evaporation time if less than the 15-min as used for the TWA calculation. References for the input data are included in [brackets].

PAC-3 = 40 mg/m^3 [PAC, 2012] for hydrofluoric acid, CASRN 7664-39-3.

MW = 20.01g/mol

VP = 50 mm Hg @ 25°C [DUF6-G-P-CLC-051]

VP = [VP_{data} / T_{data}] × 298°K

VP = (50 mm Hg)/(298°K/298°K) = 50 mm Hg

ρ = 100,000 lb /1,353 ft^3 = 73.91 lb/ft^3 [see spill data below][DUF6-G-P-CLC-051]
= 73.91 lb/ft^3 × 453.6 g/lb / 28,317 cm^3/ft^3= 1.184 g/cm^3

T = temperature of liquid = ambient 25°C = 298°K

P_a = 760 mm Hg @ ambient Standard Temperature and Pressure

h = 92.7 cm depth in dike [see liquid depth data]

u = 1.0 m/s wind speed [consistent with χ/Q wind speed assumption for F Stability]

Q' = [0.284 × u$^{0.78}$ × MW$^{2/3}$ × A × VP]/[82.05 × T]

Q'/A = [0.284 × u$^{0.78}$ × MW$^{2/3}$ × VP] / [82.05 × T]

Q'/A = [0.284 × (1.0 m/s) $^{0.78}$ × (20.01)$^{2/3}$ × (50 mm Hg)]/[82.05 × 298°K] = 4.3E-3 lb/min/ft^2

CF = - [P_a /VP] × [ln (1 – VP/P_a)]

CF = - [(760 mm Hg)/(50 mm Hg)] × [ln (1 – (50 mm Hg)/(760 mm Hg)] = 1.034

Q''/A = CF × [0.284 × u$^{0.78}$ × MW$^{2/3}$ × VP]/[82.05 × T]

Q''/A = (1.034) (4.3E-3 lb/min/ft^2) = 4.4 E-3 lb/min/ft^2

Q''/A = (4.4E-3 lb/min/ft^2)(453.6 g/lb)(min/60 s)(0.0328 ft/cm)^2 = 3.6 E-5 g/s/cm^2

t_{evap} = [ρ × h]/[Q''/A]

t_{evap} = [(1.184 g/cm^3) × (92.7 cm)]/[(3.6E-5 g/s/cm^2)] = 3.05 E+6 s (min/60 s) = 5.08 E+4 min > 15 min (no adjustment =1).

MAR = [PAC-3 × ρ × h]/[Q''/A × 3.5E-3 s/m^3] × [900/minimum (t_{evap}, 900)]

MAR = [(40 mg/m^3)(1.184 g/cm^3)(92.7 cm)]/[(3.6E-5 g/s/cm^2) × (3.5E-3 s/m^3)] × [1] × (lb/453.6 g) × (g/1,000 mg)

Conclusion: MAR = 7.7 E+4 lb or greater of 55% hydrofluoric acid, needs to be spilled to exceed PAC-3 at the CW.

For perspective, a spill of 7.7E+4 lb of 55% hydrofluoric acid translates to:

Quantity spilled = 100,000 lb = 7,765 gal [DUF6-G-P-CLC-051]

Volume spilled = 1,353 ft^3 [DUF6-G-P-CLC-051

Dike volume = 1,558 ft^3 [DUF6-G-P-CLC-051]

Dike area = 445 ft^2 [DUF6-G-P-CLC-051]

Dike height = 3.5 ft [DUF6-G-P-CLC-051]

Spill height = 3.04 ft

Spill height/Dike height = 3.04 ft/3.5 ft = 0.87. Therefore, the dike is filled to the 87% level.

To exceed High MOI consequences at 1 km, Equation 7.8-12 applies with the following inputs:

PAC-2 = 16 mg/m^3 [PAC, 2012]

χ/Q (site boundary) = 6.73E-4 s/m^3

MAR = [PAC-2 × ρ × h]/[Q''/A × χ/Q (site boundary)] × [900/minimum (t_{evap}, 900)]

MAR = [(16 mg/m^3)(1.184 g/cm^3)(92.7 cm)]/[(3.6E-5 $g/s/cm^2$)(6.73E-4 s/m^3)] × [1] × (lb/453.6 g) × (g/1,000 mg)

Conclusion: MAR = 1.6 E+5 lb or greater of 55% hydrofluoric acid, needs to be spilled to exceed PAC-2 at a 1 km site boundary distance.

The benefit of the diking in reducing the source term and therefore increasing the screening quantity threshold is clearly apparent.

8 HAZARD CONTROL SELECTION AND CLASSIFICATION

Hazard controls are those engineered and administrative measures that act to eliminate, limit, or mitigate hazards to workers, the public, or the environment. The primary purpose of the hazard and accident analysis is to select appropriate hazard controls and classify their importance to safety.

The initial identification of selection of hazard controls typically occurs as part of the HA process and is captured in the hazard evaluation table where potential means for preventing or mitigating the hazardous event are listed. Identification of hazard controls should start during the hazard identification phase and carry through the end of the hazard evaluation or accident analysis.

Depending on the scope of the HA, hazard controls may be selected from existing controls or proposed as new controls. For a planned facility or new design, the HA may be used to propose controls for the facility. For an existing facility, the HA may be used to evaluate the existing controls for the facility or recommended controls that may be needed.

In DSAs prepared for DOE HC-2 and 3 nuclear facilities, control selection is based on the unmitigated evaluation of hazardous conditions and accidents (events). An unmitigated consequence potential above a predetermined level identifies events for which SS or SC controls may be needed. The mitigated evaluation involves the functioning of designated preventive and/or mitigative hazard controls that reduce consequence, likelihood, or both.

The control selection methodology depends in part on the 10 CFR 830 Subpart B "safe harbor" methodology being applied for the development of the DSA or other safety basis document. There are differences between the guidance from DOE-STD-3009-94 Chg. Notice 3 and its successor document, DOE-STD-3009-2014, and these also are different than other safe harbor methods such as the DOE-STD-1120-2005, *Integration of Environment, Safety, and Health into Facility Disposition Activities*. Also, DOE-STD-5506-2007 identifies preferred and alternate controls for a range of hazardous conditions or DBA/EBAs that exist in many types of TRU facilities. Nonetheless, the guidance herein is general enough to apply to most control selection applications; where specific guidance from a safe harbor method is invoked, the appropriate reference is provided.

8.1 CONTROL SELECTION

8.1.1 CONTROL SELECTION PROCESS

The control selection process facilitates selection of those hazard controls that are relied on to prevent or mitigate a potential hazardous condition or accident, based on formal hazards and accident analyses. The process organizes and evaluates the initial identification of hazard controls from the hazard evaluation portion of the HA then provides supplemental or specific controls that are effective in preventing or mitigating postulated accidents from the formal accident analysis. The output is a compilation of controls that are essential for protection of the public, for co-located and facility workers, and for defense in depth.

8.1.1.1 HAZARD AND ACCIDENT ANALYSIS INPUT TO CONTROL SELECTION

The hazard evaluation includes the initial identification of hazard controls that is an integral element of most hazards evaluation techniques (see Section 2.8). There are several types of hazard controls that may be designated as part of the hazard evaluation process (e.g., "administrative" vs. "engineered" features) and various ways to organize the information.

The potential severity of each hazard or hazardous condition identified in the hazard evaluation is estimated as part of the process. Control selection as described in this section is not necessary for hazardous conditions that do not potentially impact the public, co-located workers, or facility workers. For such low-magnitude events, it is sufficient to confirm that the hazard is adequately addressed by an implemented safety management program or applicable regulatory requirements.

Once the hazard scenarios are identified, the HA team identifies potential barriers that are available to control these hazards candidate controls that are available to prevent or mitigate the postulated hazardous conditions. There are a few common practices for organizing information:

- A typical approach is to organize information into the bounding and/or representative hazardous conditions such that a common set of controls may be effective for the conditions defined. The bounding conditions facilitate the level of importance of the control set (e.g., SC); the representative conditions provide a basis for selecting the minimum set of controls that will address a common set of hazardous conditions.
- It is usual that unique conditions exist that are not completely represented by a common hazardous condition. This means that the candidate control set may be inadequate as well. In that case, those unique conditions should be evaluated as single events for which hazard controls must be determined.
- For a broad type of hazardous condition (e.g., fire events), it may be useful to represent different magnitude conditions as separate events. In this case, smaller-scale conditions may be bounding in frequency space, while larger-scale events may be bounding in consequence, or magnitude. It is appropriate to represent both events, as the candidate controls may be different for each. For example, the smaller event may rely on preventive measures (e.g., sprinklers) to keep any incipient fire small, while the larger event may rely on mitigative measures (e.g., fire-rated barriers) to reduce the consequence of an uncontrolled release of material.

From the initial identification of hazard controls and throughout the process, the focus is to determine those controls that are most effective in controlling a particular hazard in the conditions analyzed. The HA team makes a final selection of controls that are relied on to perform or maintain a safety function, including controls required to protect assumptions. Effective control sets generally follow the following recommended hierarchy from DOE-STD-3009-2014, Appendix A:

1. Engineered controls[46] that are preventive and passive;
2. Engineered controls that are preventive and active;
3. Engineered controls that are mitigative and passive;
4. Engineered controls that are mitigative and active;
5. Administrative controls that are preventive; and
6. Administrative controls that are mitigative.

[46] Engineered controls are described as "structures, systems, and components (SSCs)" in DOE-STD-3009.

While this hierarchy is preferred, it may be determined that a hazard control lower in the hierarchy is more effective, reliable, or appropriate for the facility in question and for a given scenario. In such cases, a supporting basis should be developed for the selected hazard control.

The identification of hazard controls incorporates a defense-in-depth approach that builds layers of defense against a significant release of radioactive or other hazardous materials such that no single layer of defense is completely relied upon. This does not mean that all identified controls are part of the selected set of hazard controls. The control selection process evaluates the available pool of candidate controls from the hazard and accident analyses to determine those that are the most effective, efficient, reliable, and implementable. A subset of these are designated as SC, SS, SACs, Safety Management Programs (SMPs), or other Administrative Controls.

Bounding, representative and unique hazardous conditions are candidates for formal accident analysis (see Chapter 3, Accident Analysis Overview). The accident analysis evaluates phenomenology associated with the various accident types as they apply to the specific facility or operations being analyzed. Hazard controls from the hazard evaluation should be augmented with accident-specific performance requirements and critical characteristics. In addition, the application of hazard controls to a postulated accident may demonstrate the need to supplement hazard controls or identify unique controls for a given accident sequence.

8.1.1.2 HAZARD CONTROL TYPES

Controls selected are preventive or mitigative, can be engineered or administrative, or serve to protect initial conditions or key assumptions in the analysis. Each is discussed below.

Preventive Control: A preventative control is one that prevents a hazard scenario or accident from happening or decreases its likelihood (frequency of its occurrence). It either prevents the initiation of an accident sequence, or interrupts an accident sequence before it is severe enough to significantly harm workers or the public. Prevention may also involve actions by an operator to shut down a process, close a valve, or take some other protective action. Operator actions should be sparingly relied on as a control strategy, due to inherent risk of inaction or error and overall less reliability than an engineered control. Preventive controls must be functional prior to the initiation of an event, but are not required to survive the event provided the preventive function has been performed. The identification of such features is made without regard to any possible pedigree of the feature, such as procurement level or existing safety classification. Note that the elimination of a hazard (e.g., through substitution of a non-hazardous material, or design that eliminates a hazardous process) is not typically considered a “preventive” measure, but such action falls within the definition of a hazard control, and so should be documented when performed.

Mitigative Control: A mitigative control is one that decreases the potential consequences of the hazard scenario. It acts to reduce the severity of the hazard scenario or accident by providing barriers to an uncontrolled release of hazardous material or energy, such as confinement or shielding. Mitigation may also involve actions by workers to self-protect from the hazardous condition (e.g., evacuation) even though the accident sequence may continue uninterrupted (see Section 2.5.1, Qualitative Consequences). Note that some hazardous conditions may not provide time to permit self-protective actions by workers, even if detection or monitoring capability exists.

Some controls are purely mitigative, others are purely preventative, and still others are both mitigative and preventative. Examples include:

- High efficiency particulate air (HEPA) filtration is purely mitigative.
- The administrative control of preventing the entry of explosives into a nuclear facility is purely preventive.
- Fire suppression sprinklers can be both preventive and mitigative, but not for the same scenario:
    - Reducing the probability of a small fire developing into a large one;
    - Suppression of the fire reduces the consequence of the event (mitigative).

  (In practice, sprinklers are often considered preventive, that is, the controls are based on the preventive feature of sprinklers, not the mitigative, and are credited to reduce the scenario likelihood due to the failure of sprinklers, however, this is a site- or facility-specific decision.)

In some cases, systems or features can serve different safety functions to different receptors. For example, shield walls are mitigative for co-located worker but may be preventive to facility workers by keeping them out of a high radiation area.

Engineered Control: Includes SSCs that perform a safety function by preventing or mitigating a hazard scenario (hazardous condition) or accident sequence. Engineered controls include active systems or components designed to function in the accident environment postulated, and passive features designed to prevent or mitigate uncontrolled releases. Active engineered controls typically require one or more support systems or utilities to assure performance of their safety function, and these systems thereby also become hazard controls. Passive design features are generally more reliable than active systems when their design can withstand imposed loads or other environmental conditions postulated by the hazardous condition or accident.

Detection systems require special consideration and are usually not credited in the hazard and accident analyses unless the detection systems are required to actuate safety SSCs or initiate administrative controls. They often address only the facility worker consequences or are considered to provide only defense in depth. However, a detection system may be credited to lower a likelihood or consequence under some conditions. For example, response to an alarm may be credited to reduce the potential that a small fire may become a large one and thus limit the total inventory involved. The analyst needs to be aware of limitations of detection system capabilities and take into account the possibility that the event scenario may disable the functionality of the candidate detection system. In addition, if detection systems are credited in the analysis, then alarm systems may also need to be credited as safety controls.

Administrative Controls (ACs): Are controls that are dependent on human actions. These controls are identified from the hazard evaluation and are designated as SACs, ACs, or are encompassed in safety management programs (SMPs) as committed to by a general TSR AC requirement. ACs also include other administrative features that provide the basis for safe operation of a nuclear facility, such as programs (e.g., configuration management), program elements (e.g., control of combustible materials), or requirements (e.g., criticality safety administrative control).

DOE-STD-3009 provides a listing of safety management programs for consideration. SMPs are designed to ensure a facility is operated in a manner that adequately protects workers, the public, and the environment. By definition (10 CFR 830.3), SMPs are programs that cover topics such as quality assurance, maintenance of safety systems, personnel training, conduct of operations, inadvertent criticality protection, emergency preparedness, fire protection, waste management, and radiological

protection of workers, the public, and the environment. The HA team should determine if additional safety management programs are required based on the specific hazards present (e.g., a critical lift program, an explosive safety program or experiment safety program).

Depending on the situation, some ACs that perform specific preventive or mitigative functions for accident scenarios may be credited in the hazards evaluation or accident analysis. These are more specific functions than implied by general commitments to SMPs, and they may need to be raised to a higher importance level. Some of these ACs may have critical importance similar to or the same as those that would be classified as SC or SS, if the safety functions or objectives were performed by engineered safety systems. These are called SACs. SACs are selected to provide a preventive or mitigative function for specific accident scenarios, and having a safety importance equivalent to a safety SSC. A SAC may replace or augment a safety SSC when the engineered feature is not available or does not contain required performance characteristics, or it may provide a limit or boundary condition for the hazard or accident analysis, such as a radioactive material inventory limit. Refer to DOE-STD-1186-2004, *Specific Administrative Controls*, for discussion of SAC types and examples, and to DOE-STD-3009-2014 discussions in its Appendix A, Sections A.11 and A.12 regarding SMPs and SACs, respectively.

In addition, hazard controls may include initial conditions or assumptions made that provide the bounding conditions in which hazardous conditions or accident sequences are evaluated. Initial conditions and assumptions should be explicitly identified in the event one or more of them constitute a hazard control to be further evaluated for safety classification (see Chapters 2 and 3). Controls that protect assumptions are not credited for either frequency or consequence reductions but need to be protected for basic assumptions used in the analysis (e.g., MAR) to remain valid.

8.1.1.3 USE OF RISK MATRICES FOR CONTROL SELECTION

A method to supplement control selection uses a “risk matrix” approach, encouraged by DOE-STD-3009 and DOE-STD-5506-2007. This approach begins with unmitigated risk estimates (i.e., frequency and consequence) and follows a risk ranking process to identify higher risk hazardous events and provide a qualitative tool for enhancing the selection of hazard controls. The degree to which a given hazard control is judged to be effective in performing its preventive or mitigative safety function is illustrated in the risk matrix by the movement to lower frequency and/or consequence bins as controls are applied. Although these estimates are judgment-based, consistent application provides a sound basis for comparison.

The risk ranking process bins the results of unmitigated hazard and accident analysis for the public (via the MOI receptor), co-located workers onsite, and optionally, for the facility workers. Table 8-1 (an adaptation of Table 2-10 from Chapter 2) establishes risk ranking bins that consider the consequence rankings from the Chapter 2 Table 2-8 together with the postulated accident likelihoods defined in Table 2-9. Based on these factors, an accident is ranked as Risk Class I through IV.

Table 8-1. Typical Risk Class Matrix.

Consequence					
	High	III	II	I	I
	Moderate	IV	III	II	II
	Low	IV	IV	III	III
		Beyond Extremely Unlikely	**Extremely Unlikely**	**Unlikely**	**Anticipated**

Likelihood Bins

I = Combination of conclusions from risk analysis that identify situations of major concern
II = Combination of conclusions from risk analysis that identify situations of concern
III = Combination of conclusions from risk analysis that identify situations of minor concern
IV = Combination of conclusions from risk analysis that identify situations of minimal concern

Risk Class I events for the public are addressed by hazard controls that are designated as SC SSCs or SACs, and by associated TSRs (see Section 8.2, Safety Classification) for radiological consequences or SS SSCs or SACs for chemical exposures.[47] Operational accidents resulting in high offsite radiological consequences from the hazard evaluation are moved forward into accident analysis for determination of safety classification, without consideration of likelihood. SS controls may also be warranted for protection of the public as discussed in Section 8.2.2.

Risk Class I events for the co-located worker and Risk Class II events for all receptors, are addressed by hazard controls for which consideration as SS SSCs, SACs, and by associated TSRs should be made. The consideration of a SS hazard control is based on the effectiveness and feasibility of the controls along with the identified features and layers of defense in depth. Risk Class II events resulting in high offsite radiological consequence are included in subsequent accident analysis for determination of safety classification, without consideration of likelihood.

In essence, controls are considered for any unmitigated Risk Class I/II events. Preventive controls applied to the initial unmitigated Risk Class I/II event may suffice to prevent the event. Mitigative controls applied to the initial unmitigated Risk Class I/II event should reduce the event consequence to an acceptable value (e.g., below the EG). In some cases, more than one control may be required to reduce the consequence and/or likelihood from Risk Class I/II to Risk Class III or IV depending on its reliability or efficiency.

[47] For offsite public protection, safety class SSCs, SACs, and TSRs are established for radiological events that exceed or challenge the 25 rem Evaluation Guideline (regardless of frequency).

Risk Class III – Consider defense in depth hazard controls or safety management programs to reduce risk to Risk Class IV. Risk Class III events are generally addressed by SMPs or other Administrative Controls, however, they may need further evaluation of the need for SS controls for high-consequence operational events judged to be beyond extremely unlikely before crediting preventive controls. These events may also be considered for defense-in-depth SSCs in unique cases.

Risk Class IV – No additional hazard control measures apply.

Facility workers are sometimes not included in the risk matrix approach, because the control selection process may be binary: a significant hazard requires a SS SSC, SAC, or SMP that is protected by a TSR; a lesser hazard is generally addressed by an SMP or other Administrative Control.

When the risk matrix approach is *not* used, the designation of hazard controls as SC, SS, or SACs follow the guidance provided in Section 8.2 without the enhancement of a risk ranking to demonstrate control effectiveness.

8.1.2 CONTROL SELECTION CONSIDERATIONS

The hazard controls compiled from the hazards and accident analyses form the basis for control selection. Candidate hazard controls should receive specific considerations from operations, engineering, maintenance, and safety basis engineers. These should include the following:

Effectiveness

- Does the control function in the accident environment postulated? Are specific qualifications needed?
- Is the control most effective in reducing risk?
- How far from the hazard are the controls located; i.e., the closest controls may be more effective?
- Where is the control on the control hierarchy? Is the selection justified?

Efficiency

- Is the control effective for several accidents or hazardous conditions? Does it provide defense in depth or worker safety for multiple events?
- Is the control dependent on support systems or utilities? Are these also qualified for their environment?
- Does the control minimize the number of active or supporting safety features?
- Does the control provide functional diversity or redundancy?

Implementation & Reliability

- Does the control preclude the need for compensating measures or features?
- Is the control simple or straightforward to establish, surveil, and maintain?
- Is the control insensitive to random failure or false indication?
- Does the control provide advance notification of trouble (i.e., accident does not initiate upon failure)?
- Does the control incorporate human factors to ensure reliable performance or to facilitate surveillance and maintenance?

Functional and environmental requirements should be defined from the accident analysis to develop the performance specifications for equipment relied upon in mitigating or preventing the accident under conditions existing during and following the DBA/EBA. Consider the following:

- The time-dependent temperature and pressure at the location of the equipment during the most severe DBA/EBA.
- The humidity during the DBA/EBA.
- Chemical effects especially if the composition of the chemicals can be affected by equipment malfunctions.
- The radiation environment associated with the DBA/EBA during which the equipment is required to remain functional.
- Aging of equipment could cause degradation which can have an effect on the functional capability of the equipment.
- Synergistic effects are to be considered when these effects are believed to have a significant effect on equipment performance.
- Interactions with and impacts from other systems (e.g., filter loadings).

Selected hazard controls should reflect a robust, defense in depth approach to postulated hazardous conditions and accidents. Redundancy and overlap are encouraged.

8.2 SAFETY CLASSIFICATION OF CONTROLS

8.2.1 SAFETY CLASS DESIGNATION

DOE-STD-3009 defines an EG of 25 rem TED to the public and requires designation of SC SSC to mitigate the dose to below the EG. The dose estimates to be compared to it are those received by a hypothetical MOI or public receptor at the site boundary from a DBA or EBA causing an unmitigated release of radioactive material that challenge the EG (see DOE-STD-3009-2014 Section 3.3.1 regarding MOI unmitigated doses exceeding 5 rem TED that may challenge the EG). The control selection process of Section 8.1 will result in the identification of hazard control(s) that will prevent or mitigate DBA/EBA consequences to less than the EG. Additional controls to further reduce consequences to well below the EG or to provide defense in depth may be candidates for SS designation as discussed in Section 8.2.2.

8.2.2 SAFETY SIGNIFICANT (SS) DESIGNATION

The designation of SS SSC is based on hazard controls selected for co-located or facility worker safety or for defense in depth. Criteria from Section 3.3 of DOE-STD-3009-2014 for selecting SS controls are based on four criteria: 1) protecting co-located workers at 100m that receive an unmitigated dose of 100 rem TED; 2) protection of the public from releases of hazardous chemicals; 3) protecting facility workers from significant injury or fatality, or from exposure to radiological or hazardous material; or 4) determined to be a major contributor to defense in depth that provides additional protection of the public and the environment. These criteria are more specific to the criteria of DOE-STD-3009-94 CN3.

8.2.3 CLASSIFICATION OF OTHER HAZARD CONTROLS

The hazard evaluation process may identify preventive or mitigative controls that do not rise to the level of SC or SS controls but still enhance the safety of the facility. These controls are identified in the hazard evaluation table and may be determined to be important to defense in depth or worker safety, but not explicitly credited with a SC or SS designation. Such controls are maintained in accordance with SMPs or other Administrative Controls and the Unreviewed Safety Question process (which includes

consideration of equipment important to safety as described in the DOE Guide G 424.1B, Implementation Guide for Use in Addressing Unreviewed Safety Question Requirements).

Other hazard controls may also include specific controls required by DOE in its Safety Evaluation Report (see DOE-STD-1104-2014, *Review and Approval of Nuclear Facility Safety Basis and Safety Design Basis Documents*, for further guidance). These controls do not require SC or SS designation unless directed by the DOE.

8.3 EVALUATION OF EXISTING FACILITIES WITH MITIGATED OFFSITE CONSEQUENCE ESTIMATES OVER THE EVALUATION GUIDELINE

There is a special case if the MOI consequences cannot be prevented or effectively reduced to below the EG. This "Over the EG" evaluation is required for all existing DOE facilities with mitigated offsite consequence estimates over the EG, regardless of the safe harbor used. This "Over the EG" evaluation is expected to be applied rarely. The following additional guidance and methods are provided for effective implementation, when used.

DOE-STD-3009-2014 Section 3.3.1, SC Controls, establishes requirements for existing facilities with mitigated offsite consequence estimates over the EG where the EBA is not prevented. In addition, the DOE review and approval of the DSA includes DOE requirements and guidance for this situation, as described in the DOE-STD-1104-2014, *Review and Approval of Nuclear Facility Safety Basis and Safety Design Basis Documents*, Section 4.9, Existing Facilities with Mitigated Offsite Consequence Estimates over the EG. The requirements and guidance from both standards are summarized on Table 8-2, along with additional clarifications and guidance.

Table 8-2. Over the EG Evaluation.

DOE-STD-3009-2014 Section 3.3.1, SC Controls	DOE-STD-1104-2014 Section 4.9, Existing Facilities with Mitigated Offsite Consequence Estimates over the EG	Additional Clarifications and Guidance
In circumstances where no viable control strategy exists in an existing facility to prevent or mitigate the consequence of one or more of the accident scenarios from exceeding the EG, the following information shall be provided in the DSA, or an attachment to the DSA:	This section provides specific approval bases for rare situations where SC controls are not provided to prevent or mitigate offsite doses below the EG. In circumstances where no viable control strategy exists in an existing facility to prevent or mitigate the consequence of one or more of the accident scenarios from exceeding the EG, DOE shall verify that information is included in the DSA, or an attachment to the DSA, that is consistent with the requirements described in Section 3.3.1 of DOE-STD-3009-2014. The following criteria should be used to judge technical adequacy of DSA information:	The DSA Section [3.4.3.X.5], Summary of SC and SS SSCs, SACs, and TSR Controls, may be an appropriate location to document the "Over the EG" evaluation, or depending on its complexity, an appendix may be more suitable that is referenced in this section of the EBA evaluation. An executive summary of this evaluation should be included in the DSA Section [E.6], Safety Analysis Conclusions.
• Identification of the	• Accidents that cannot be mitigated	Accidents that cannot be mitigated below the EG or prevented, are explicitly

DOE-STD-3009-2014 Section 3.3.1, SC Controls	DOE-STD-1104-2014 Section 4.9, Existing Facilities with Mitigated Offsite Consequence Estimates over the EG	Additional Clarifications and Guidance
accidents that cannot be mitigated or prevented, including the likelihood of the event(s) and the mitigated consequences associated with the event(s), based on calculations following the methodology described in this Standard.	below the EG or prevented, are explicitly identified, including the likelihood of the event(s) and the mitigated consequences associated with the event(s). • Accidents likelihood and consequences are determined in accordance with the DSA safe harbor methodology (e.g., Section 3.2 of DOE-STD-3009-2014). This includes source term estimates, dispersion analysis methodology, and dose consequence assumptions.	identified in the DSA accident analysis of the EBA and further evaluated. An example of an EBA that cannot be prevented or mitigated below the EG could be a collapse of the structure from a DOE Order O 420.1C design basis earthquake that has a greater magnitude due to a 10-year updated assessment of seismic hazards that is being evaluated for an existing facility. Accident likelihood and consequences are summarized from information that is already part of the DSA accident analysis for the EBA such as Sections [3.4.3.X.1] Scenario Development, [3.4.3.X.2] Source Term Analysis, and [3.4.3.X.3] Consequence Analysis
• A discussion of the credited controls, including their reliability and adequacy, and an analysis ….	• The reliability and adequacy of credited controls is addressed (e.g., consistent with DOESTD-3009-2014 system evaluation requirements for SC SSCs, as applicable).	This should include identifying the safety function of the credited control to prevent or mitigate the EBA as described in the DSA Chapter 4 along with a description on how they prevent the event, or reduce its likelihood or consequences. The reliability and adequacy of credited controls should be described, along with discussions of potential failure modes of these credited controls, and any compensatory measures established. This information is already part of the DSA Chapter 4 and is summarized in the "Over the EG" evaluation. Significant contributors to uncertainty in both the likelihood and consequence evaluations associated with the credited controls should be identified and characterized.
• A discussion of the available controls[60] that could reduce the likelihood and/or consequences of the associated accident(s), including their potential failure modes, their potential impact on accident mitigation, any relevant cost/benefit results, and the reasons why they are not selected as credited controls to reduce the consequences to below the EG. [60] Controls considered but not	• Controls considered (SSCs and SACs) but not identified as SC that could further reduce the likelihood and/or consequences of the associated accident(s) are described in the DSA. The impact of these controls on accident mitigation, as well as the rationale for not classifying these controls as SC should be presented. Discussions of potential failure modes of SSCs and any relevant cost/benefit results are included.	The footnote #60 clarifies other available or new controls that were considered, which could include additional MAR restriction, operational restrictions, and/or additional compensatory measures. Those existing controls (SSCs and ACs) considered but not identified as SC are identified and described, including their impact on accident mitigation or further reduction in the likelihood. The rationale for not crediting and classifying these controls as SC should be provided, e.g., lack of reliability of the SSC that cannot be augmented with compensatory measures to provide a SC safety function, effectiveness of the control, human

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identified as SC controls include existing controls that were not elevated to SC status, as well as new controls that could have been established through changes to the facility or to its operations. This includes controls to reduce the radiological source term. Controls can include SSCs and ACs.		factors considerations to implement the AC as a SAC, feasibility of implementing a new control that was considered, etc. Discussions of potential failure modes of these potentially available controls and any relevant cost/benefit results should be included in the discussion. This section addresses controls that were consider that can be readily implemented rather than those additional controls that are being committed to and identified in the next section on planned operational or safety improvements.
• A discussion of any planned operational or safety improvements, including potential facility modifications, reductions in MAR, and/or additional compensatory measures, and associated schedules, to further reduce the likelihood and/or mitigate consequences of an accident. Note: Where DOE has accepted a path forward, the path forward may be used to support this discussion.	• Planned operational or safety improvements are presented and include potential facility modifications, removal of MAR, packaging of MAR into containers, operational restrictions, and/or additional compensatory measures, and associated schedules, to further reduce the likelihood and/or mitigate consequences of an accident.	This section addresses additional measures that are being committed to, including new preventive or mitigative controls that can't be readily implemented, and are identified as planned operational or safety improvements. The STD-1104 guidance identifies some of the potential improvements, and discussion of associated schedules. Where compensatory measures that are not readily implementable will be provided, these should be clearly identified and summarized.
• A discussion of … an analysis of the expected likelihood and mitigated offsite consequence estimates of the associated accident(s). The analysis should include a discussion of the significant contributors to uncertainties in both the likelihood and consequence evaluations. The analysis should compare the risk (i.e., likelihood and consequences) based on calculations performed per Section 3.2 of this Standard to the risk calculated using mean or best estimate values for source-term and dispersion input parameters (with supporting technical	• Mean or best estimate values used for source-term and dispersion input parameters that are part of comparative analyses (e.g., as described in DOE-STD-3009-2014, Section 3.3.1, bullet #2) have a valid technical basis that includes logical assumptions that are based on experiments, tests, or sound engineering judgment. The analysis describes the significant contributors to uncertainties in both the likelihood and consequence evaluations. The mean or best estimate calculation is used to provide perspective regarding the degree of conservatism that is imbedded in the consequence calculation. • A qualitative or semi-quantitative comparison of the facility risk from identified scenarios and	A more realistic risk assessment of the EBA provides an important perspective for the contractor and DOE acceptance of risk associated with not preventing or mitigating the EBA to below the EG. This section should present any quantitative or qualitative evaluations of the risks and document the basis for risk acceptance. DOE Policy 420.1, *Nuclear Safety Policy*, establishes two goals (not requirements) for public protection: 1) The risk to an average individual in the vicinity of a DOE nuclear facility for prompt fatalities that might result from accidents should not exceed one-tenth of one percent (0.1%) of the sum of prompt fatality risks resulting from other accidents to which members of the population are generally exposed. For evaluation purposes, individuals are assumed to be located within one

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basis). • A qualitative or semi-quantitative comparison of the facility risk from the identified scenarios and total facility risk (i.e., cumulative risk estimate for facility accidents) with the quantitative safety objectives provided in DOE Policy 420.1. Discuss the level of risk and the basis why this risk is acceptable, taking into account an evaluation of available alternatives, the benefits to the public of the alternatives, and the costs to the public of the alternatives.	cumulative facility risk (for all facility operations) estimate for facility accidents (including the results in response to the second bullet) is presented along with a comparison to the quantitative safety objectives provided in DOE Policy 420.1. A discussion of the level of risk and the basis why this risk is acceptable is provided, taking into account an evaluation of available alternatives, the benefits to the public of the alternatives, and the costs to the public of the alternatives.	mile of the site boundary. 2) The risk to the population in the area of a DOE nuclear facility for cancer fatalities that might result from operations should not exceed one-tenth of one percent (0.1%) of the sum of all cancer fatality risks resulting from all other causes. For evaluation purposes, individuals are assumed to be located within 10 miles of the site boundary Site-specific or locality-specific quantitative data should be used whenever available. For the DOE Policy 420.1 risk perspectives, the risk from the facility includes the full-spectrum of operations, including normal operations, operational accidents, external events, and NPH events. Other accidents/events could be presented for perspective, such as risk of a prompt fatality or latent cancer fatalities from aircraft crashes, dam failures, fires, explosions, chlorine releases, and natural phenomena events as previously evaluated for the nuclear reactor industry.
The level of detail for the analysis above may be implemented on a graded approach that considers the remaining operating life of the facility and the extent of deviation from the EG. For example, where the remaining lifetime of the facility is less than five years, a detailed analysis using mean values and making comparisons to the DOE Policy 420.1 safety goals is not necessary, but a discussion of available controls considered and planned safety improvements and associated schedules is expected.	The level of detail for the analysis above may be graded based on the remaining operating life of the facility and the extent of deviation from the EG. The DOE review should consider the best available mission statements related to facility operations and determine whether there is a high likelihood that projected estimates of remaining operational life are supported and commensurate with details provided in the DSA. Likewise, the extent of deviation from the EG for mitigated consequences estimates should be explicitly addressed by the DOE review team and discussed in the SER as part of the approval basis. Planned operational or safety improvements, including compensatory measures, should be pursued where the deviation from the EG is significant (such as where the mitigated offsite dose estimate is more than two to three times greater than the EG), the remaining life is significant (such as more than 1-3	

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	years), and the likelihood is significant (such as more often than 1 in 10^6 years). Compensatory measures should be commensurate with the significance of the deviation from the EG, the likelihood of accident(s), and the length of time needed to resolve the condition.	

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Note: *R = Reaffirmed, W = Withdrawn*

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APPENDIX A HAZARD ANALYSIS TABLE DEVELOPMENT

This appendix provides examples of the documentation of hazard analysis (HA) results to support development of a safety design basis document.[48] Although other formats may be used to capture this information, a table format has been selected to capture the requirements. This table is prepared with columns or sections corresponding to the headings of sections A.1 through A.10 of this appendix. Sections A.1 through A.10 describe the content of the corresponding column of the table for each HA accident scenario. This format can be used to document the Preliminary Hazard Analysis (PHA) developed during the conceptual design, or the hazard evaluation at the process level developed during the preliminary or final design. It should be updated as the design matures through final design and transition to operations. As this documentation is a key element of the safety basis, it is maintained after project transition to operations as a basis document for the final Documented Safety Analysis (DSA) or a supporting document for the DSA. Although alternate formats may be used to capture and retrieve this information (e.g., a database), the material identified in this appendix is required to be developed. The appropriate HA technique is selected that will be sufficiently detailed to provide a comprehensive examination of the hazards associated with the facility given the complexity of the operation and degree of design maturity and develop the information required by this appendix. See Chapter 2, "Hazard Analysis Process," for further discussion of the hazard evaluations.

A.1 SCENARIO DESCRIPTION

Describe each postulated accident scenario that could lead to the release of hazardous materials. The description should appropriately describe the mechanism(s) that lead to the release of hazardous material. Examples include spills, over-pressurization, deflagration, fire, and similar mechanisms. This description should be as complete as possible for the current design stage to facilitate use in developing controls and their functional and design requirements, as well as support unreviewed safety question determinations during operation.

The description should also include an explicit description or reference to the Material at Risk (MAR), chemical or radiological, as appropriate, involved with or potentially affected in the scenario. As appropriate, describe the effect that the initiating event has on the major facility structures, systems, and components (SSCs), primarily those that could release energy or radioactive/hazardous material.

Scenarios identified during the PHA process for conceptual design will be facility-level or major MAR location events for the facility. The key at conceptual design is to review the release mechanisms for the major MAR inventory locations sufficiently to ensure that high-cost safety functions have been identified and included in the project design and cost estimates.

A.2 INITIATING EVENT FREQUENCY

Provide the conservatively assigned likelihood or frequency of the initiating event or of the accident itself, where a series of events contribute to a release of material, such as fire events or a natural phenomena hazard (NPH) followed by spill or fire. The goal is to qualitatively bin the event frequency sufficiently to aid in event prevention and mitigation strategy selection (e.g., Anticipated, Unlikely, Extremely Unlikely, and Beyond Extremely Unlikely). The initiating event frequency should be consistently applied as the initiator frequency.

[48] This appendix has been updated from Appendix G, Hazard Analysis Table Development, of DOE-STD-1189-2008, *Integration of Safety into the Design Process*.

A.3 UNMITIGATED CONSEQUENCE EVALUATION

Describe the hazardous material release with respect to facility workers in each unique location, co-located workers, and offsite personnel that are affected.

Identify the consequence to each receptor for the event. Although detailed knowledge may not be available, it is important to make appropriately conservative determinations of dose consequences so that the safety control selection is also conservative. When available, quantitative information should be used as a guide for consequences due to chemical or radioactive material releases based on bounding assumptions. However, binning into defined ranges is preferred and specific values are not required. This is especially true for worker consequences, which are intended to be qualitative.

Assumptions established as a part of the consequence determination should be identified, in order to provide the technical basis for parameters of interest. Particularly, the hazardous material inventory, airborne release fraction (ARF), and damage ratio and their bases should be described. Reference appropriate calculations that support the identified consequence, when they have been performed.

While an assessment of the level of accident consequences is necessary to determine the need and safety classification of SSCs providing protection of facility workers, these assessments should be, at most, "back of the envelope" calculations, to give a sense of the order of magnitude of the doses. In the case of facility worker consequences, especially immediately involved workers, the assumptions that could be made in the course of any more definitive calculations could easily affect the results by orders of magnitude. Thus, such calculations, if used to apply a numerical criterion, would divert attention from good safety decisions to arguments about the calculations and assumptions during the review.

A.4 SAFETY FUNCTIONS

Based on the release event description, list the safety functions needed to prevent or mitigate the MAR release event. The safety function is a qualitative statement of a function that prevents an initiating event or mitigates the outcome. The safety function is the desired result from an administrative action or a SSC and should be stated in a general way, while still describing the preventative or mitigative action. For conceptual design, the safety function in this entry should not specify a SSC or otherwise state how the safety function is satisfied. This has two purposes: (1) it provides flexibility in SSC selections; and (2) it ensures that the specific functional and design attributes for a selected SSC fulfill the defined higher-level safety function identified for the event.

- The safety function statement serves as a link between the HA and the safety SSCs by defining the overall objective and top-level functional requirements for the SSC. The top-level functional requirements are those performance parameters of special importance because they are specifically relied upon in the safety analysis.
- Safety functions should not be predicated on the SSCs or Specific Administrative Controls (SACs) that may be chosen to provide the function. The opportunity for novel and improved solutions is reduced when the solution drives the requirement.
- The safety function statement for each SSC or SAC within a facility should be sufficiently specific to enable assigning appropriate supporting SACs or SSCs to fulfill the needed safety function completely.
- Safety functions should include the following:
  - situations and any general accident types during which the function is required to be met;
  - specific functional needs that prevent, detect, or mitigate an event; and

- sufficient description to enable clear functional requirements and later, design requirements and acceptance limits for those SSCs ultimately chosen to meet the top-tier safety function described.

A.5 PREVENTIVE FEATURES (DESIGN AND ADMINISTRATIVE)

List all SSCs and administrative controls (ACs) that have the potential to prevent the event initiator or reduce the frequency of accident progression. This should be consistent with the approach (initiator or event progression) used to determine the frequency (see A.3 above). In the early stages of the conceptual design process, this listing may include SSCs that are currently not part of the conceptual design; but, if selected, would be added to the conceptual design. Initiating events that cannot be prevented, such as NPH events that lead to a release, should be listed as not applicable (N/A).

This listing will be used to select the suite of safety systems, important to safety systems, and/or defense in depth SSCs for the MAR release events. When complete at Critical Decision-1, only SSCs actually present in the conceptual design should be included.

A.6 METHOD OF DETECTION

Identify all SSCs and administrative functions that could detect the event. This would include SSCs that may or may not be selected, as well as direct observation by the operations staff. In the early stages of the conceptual design process, this listing may include SSCs that are currently not part of the conceptual design.

Although the instrumentation systems are generally not well defined at the conceptual design stage, the expected detection methods to be included in the preliminary design should be included in the PHA tables. This provides a means for providing future design guidance and a basis for estimating equipment costs, in particular for systems that may be a high-cost driver for the project. An example of this is when instrument air would be needed to support a safety class detection system. This could lead to the compressor systems for the air being SC and, ultimately, becoming a high-cost impact to the project. Therefore, it is important in conceptual design to consider this sufficiently to capture any major cost needs at a minimum during conceptual design. For prevention, this will identify instrumentation that will detect the event is about to occur.

When complete at Conceptual Design-1, only SSCs in the conceptual design should be included.

A.7 MITIGATIVE FEATURES (DESIGN AND ADMINISTRATIVE)

List all SSCs and ACs that potentially could mitigate the event by limiting the consequences after the event has happened. In early stages of the conceptual design process, this listing may include SSCs that are not currently part of the conceptual design. Consideration of the following mitigative systems and design features should be included:

- fire suppression/detection;
- confinement ventilation;
- emergency power;
- nuclear criticality design features and/or alarms, consistent with the guidance in DOE-STD-3007-2007, *Guidelines for Preparing Criticality Safety Evaluations at Department of Energy Nonreactor Nuclear Facilities* (if the facility will have at least a minimum critical mass of fissionable material);
- seismic design, including addressing level of confinement for primary confinement system (building structure); and
- flammable gas controls.

When complete at Conceptual Design-1, only SSCs in the conceptual design should be included.

A.8 SSC SAFETY CONTROL SUITE AND SAFETY FUNCTIONS

This section summarizes the suite of hazard controls, including safety SSCs that will be relied upon to detect, prevent, or mitigate each event. DOE-STD-1189-2008, *Integration of Safety into the Design Process*, and the requirements in DOE O 420.1C, *Facility Safety*, are key inputs to the identification of the safety control suite selected, the functional classification of selected SSCs, and the NPH requirements.

The hazard controls identified in the conceptual design PHA are preliminary until accident analysis confirms their need and validates that they are the correct and adequate controls for the event. The identification of the hazard controls should be reasonably conservative to establish an appropriate cost and schedule basis for the project. The selection of hazard controls is iterative. If, after selecting one or more of the available controls, the mitigated consequence still exceeds the applicable threshold criteria, additional controls are selected or identified and classified accordingly. In some cases, it may be prudent to use multiple controls where only one may be required to effectively prevent or mitigate the event. Where SACs are included in lieu of an SSC, an explanation should be provided. The final list of selected controls should be provided in the PHA tables.

A.9 MITIGATED CONSEQUENCES

The estimated consequences for the identified receptor after applying the hazard controls are listed. During conceptual design, the quantitative results for the unmitigated events may not be known. In this case, the mitigated results are qualitatively estimated based on a reduction factor on the unmitigated consequences. Once the accident analysis is performed, this section will be updated with the results of this quantitative analysis. If an event is prevented by application of the hazard controls, i.e., the preventive controls eliminate the hazard or terminate the hazard or accident scenario and prevent a release of radioactive or other hazardous materials as described in DOE-STD-3009-2014, *Preparation of Nonreactor Nuclear Facility Documented Safety Analysis*, Section 3.3.1, “Safety Class Controls,” this result is reported in the mitigated consequence column as “prevented.”

This information is input to the demonstration of sufficiency of the control suite selected in the safety design basis documents.

A.10 PLANNED ANALYSES, ASSUMPTIONS AND RISK/OPPORTUNITY IDENTIFICATION

List remaining analysis or assumption validations and risk/opportunities associated with the selected strategies. The bounding events that require further analysis are identified in the PHA. The events selected are grouped into accidents that are representative of the hazardous conditions. The accidents are defined in such a way as to predict the consequences so as to be bounding for all similar events with the same control suite. Other events, for which the need for hazard controls (or the functional classification or NPH criteria) was not obvious, should also be evaluated in more detail (potentially quantitatively) later in the preliminary design phase. This will ensure that the selection for each safety control has a firm basis and that the assigned functional classifications and design criteria are also based on objective determinations.

Assumptions used in the PHA process need to be verified as the design matures. As an example, the facility MAR used in the hazards analysis may have been based on a highly conservative assessment of tank volumes and concentrations. When the final documents and process and instrumentation drawings (P&IDs) are issued in preliminary design, the actual tank volumes should be used in the accident analyses. Other assumptions concerning the event progression, such as impact to SSCs, are also verified. Remaining evaluations to be performed are identified.

It is essential that potential risks and opportunities to be fed into the Risk and Opportunity Assessment (R&OA) as the safety control suite is selected. The presentation of risks and opportunities associated with the strategies are essential facets for risk-informed decision making in the authorization for the project to proceed to preliminary design.

A.11 HAZARDS EVALUATION TABLE

The final hazard evaluation table (or equivalent) includes the items discussed above and portrays the hazard scenarios associated with the facility and the safety systems that will detect, mitigate, or prevent unacceptable MAR releases. The table should present the logical binning of events evaluated (e.g., fire, operational events, fire, NPH). In essence, these scenarios are those from which the design basis accidents (DBAs) for the facility are selected. The table provides valuable information to be included in the risk and opportunities analysis and needed studies to validate key assumptions. This table portrays the functional safety attributes for the facility safety systems that are to be incorporated into the conceptual design and cost estimates. The final table will be used as the foundation for development of the safety basis design documents, which will describe the events evaluated and the safety control suite in a format that can be used as the foundation for a final DSA for the facility.

APPENDIX B FIRE ANALYSIS

This section presents summary information needed to understand and evaluate the progression and severity of fire events. The analytical methods presented in the following subsections focus on simple fire phenomena that lends itself to hand calculation. Complex models involving multiple rooms and openings or the need to understand detailed heat transfer characteristics can be more effectively modeled using computer based analysis. The Consolidated Model of Fire and Smoke Transport (CFAST) is a Central Registry Toolbox Code approved for use in safety basis development; an EH guide is available for further information (DOE-EH-4.2.1.4, *CFAST Computer Code Application Guidance for Documented Safety Analysis)*.

This appendix provides information on the following topics related to fire analysis:

- Theory of Fire Growth and Progression
- Calculation Methods of Fire Aspects Supporting Documented Safety Analysis (DSA) Development include:
    - Heat Release Rate (HRR)
    - Flame Height
    - Enclosure Fire Dynamics
    - Flashover
    - Solid Fuel Ignition and Radiant Heating
- Wildland Fire Event Description and Analysis

B.1 FIRE IGNITION, GROWTH, AND PROGRESSION

All fire scenarios can be summarized into four distinct regimes: ignition, growth, fully developed, and decay. Ignition can occur when flammable vapors are present in sufficient quantity to be ignited; this can occur due to the release of a flammable gas, spillage of a flammable liquid, or the heating of a combustible liquid or solid material (pyrolysis). Following ignition of the initial fuel source, neighboring materials can be heated through direct flame impingement and/or heat transfer causing propagation and overall growth of the fire.

A fire can become fully developed when it reaches either a fuel-limited or ventilation-limited state. Scenarios, such as an outdoor pool fire, reach a fuel-limited state when the entire surface area becomes involved and sufficient oxidant, usually air, is available for combustion. Ventilation-limited fires occur in enclosures where sufficient openings are not available to support the burning of all combustibles in the enclosure. A fire can remain in a fully-developed state until all available combustibles are burned or outside intervention takes place (e.g., fire department response, fire suppression system, etc.). Intervention of the fire can result in extinguishment or control. Figure B-1 shows the four fire regimes and the effects of intervention as a function of HRR and time.

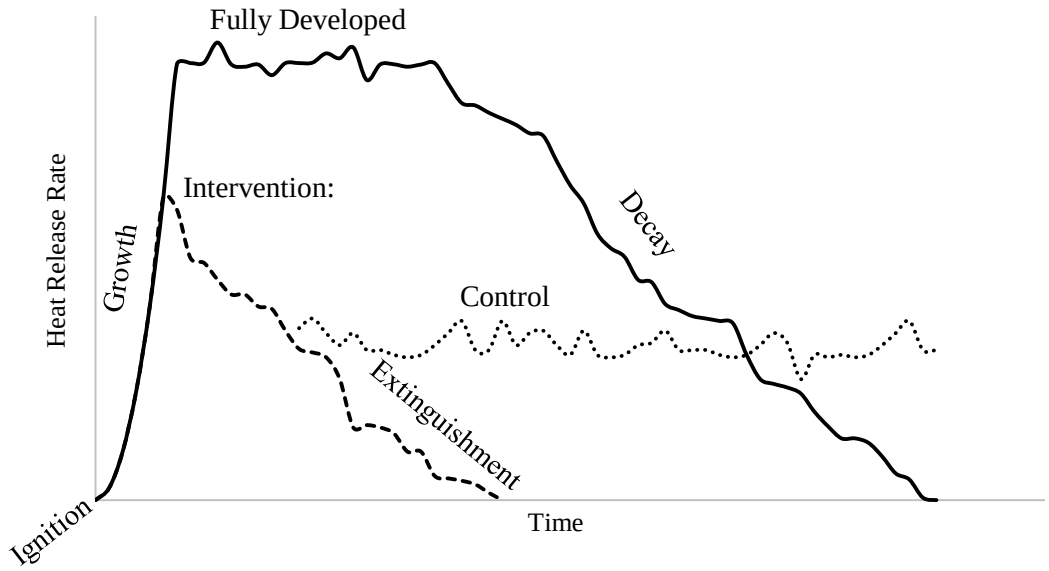


Figure B-1. Fire Growth Model.

B.2 CALCULATION METHODS FOR FIRE ANALYSIS

Correlations based on experiments and testing for numerous phenomena related to fire have been developed and have been proven to be reasonable estimates for modeling and analysis. Much of these can be applied as hand calculations. This sub section introduces some basic calculation methods commonly used for accident analysis. It should be noted that extensive analysis techniques are documented and available in various National Fire Protection Association standards and its Handbook, in the Society of Fire Protection Engineers Handbook (SPFE, 2008), and in other fire protection engineering references; those presented here are not meant to limit what should be used in the DOE complex nor will they be applicable in every scenario. Also, many scenarios are of sufficient complexity to justify the use of computer models such as CFAST. The Nuclear Regulatory Commission has issued NUREG-1805, *Fire Dynamics Tools (FDT^s): Quantitative Fire Hazard Analysis Methods for the U.S. Nuclear Regulatory Commission Fire Protection Inspection Program*. This document has similar information to the SFPE Handbook and is available for download from the NRC. In addition, there are spreadsheets associated with NUREG-1805, available on line, that allow the user to input heat, diameter and fuel type and the spreadsheet does the calculation and provides a text listing of the equation being solved. Application of these spreadsheets are subject to the DOE SQA requirements as discussed in Section 3.5 of this Handbook.

B.2.1 HEAT RELEASE RATE (HRR)

For most fire scenarios, the combustible loading and configuration will be well established. It is usually necessary to understand the unmitigated fire potential in terms of HRR. The two examples that follow detail common methods for determining the potential HRR for a fire involving liquids and solids. To determine the maximum potential HRR, the fires are assumed to be fuel-limited with adequate oxygen to support full involvement of the fuel. Note that this assumption will produce higher mass-loss rates, and thus shorter durations, than a ventilation-limited fire.

B.2.1.1 POOL FIRE HEAT RELEASE RATE

Liquid pool fires can occur following a spill or leak of flammable or combustible liquid. Common scenarios include:

- Spill into a diked area or sump followed by ignition;
- An unconstrained spill onto a hard surface;
- An unconstrained spill onto a permeable surface (e.g., soil); and
- A flowing spill that is ignited.

Methods to establish the HRR for these scenarios are described in *The SFPE Fire Protection Handbook of Fire Protection Engineering* (SFPE, 2008). Contained spills are covered in the Handbook Section 1, Chapter 3, "Heat Release Rates." The other three scenarios are described in Section 2, Chapter 15, "Liquid Fuel Fires."

Typically, pool fires are assumed to be circular; it is common practice to estimate arbitrarily shaped fires using an equivalent area circle (e.g., a square, odd geometry with a width to height ratio of approximately 1). Highly elongated shapes are not applicable to the methods described below. The SFPE Fire Protection Handbook can also be consulted for its equation and guidance for the diameter of a pool for the case where the pool is ignited immediately after the spill starts which is determined by the mass loss rate from the burning liquid when in equilibrium with the spill rate.

<u>Example:</u> A 100 gal (0.38 m^3) kerosene spill, which is contained by a 3 m by 5 m diked area, is ignited. The objective is to estimate the HRR from the burning pool. Because the diked area is rectangular, an effective pool diameter needs to be estimated.

$$D_{eff} = \sqrt{\frac{4A}{\pi}} = \sqrt{\frac{4(3\,m)(5\,m)}{\pi}} = 4.4\,m \qquad \textbf{Equation B-1}$$

Where:

D_{eff} effective pool diameter (m)

A pool fire area (m^2)

The HRR is estimated from:

$$\dot{q} = \Delta h_c \dot{m}''_{\infty}(1 - e^{-k\beta D}) \times A \qquad \textbf{Equation B-2}$$

Where:

$\dot{q}$ HRR (MW)

Δh_c net heat of combustion (MJ/kg)

$\dot{m}''_{\infty}$ mass loss rate per unit area (kg m^{-2} s^{-1})

$k\beta$ extinction absorption coefficient and beam length correction (m^{-1})

D= Effective pool fire diameter (m)

For kerosene, Equation B-2 becomes:

$$\dot{q} = (43.7\,\mathrm{MJ/kg})\left(0.039\frac{\mathrm{kg}}{\mathrm{m}^2\cdot\mathrm{s}}\right)\left(1-e^{-(3.5\,\mathrm{m}^{-1})(4.4\,\mathrm{m})}\right)[(3\,\mathrm{m})(5\,\mathrm{m})] = 25.6\,\mathrm{MW}$$ **Equation B-3**

For a uniform pool depth, the approximate burn duration for the fire is:

$$t = \frac{\rho V}{\dot{m}''_{\infty}(1-e^{-k\beta D})\times A}$$ **Equation B-4**

Where:

t is the fire duration (seconds)

ρ is the liquid density (kg/m^3)

V is the spill volume (m^3)

For the postulated 100 gal spill, the fire duration from Equation B-4 is:

$$t = \frac{\left(820\frac{\mathrm{kg}}{\mathrm{m}^3}\right)(0.38\,\mathrm{m}^3)}{\left(0.039\frac{\mathrm{kg}}{\mathrm{m}^2\cdot\mathrm{s}}\right)\left[1-e^{-\left(3.5\frac{1}{\mathrm{m}}\right)(4.4\,\mathrm{m})}\right][(3\,\mathrm{m})(5\,\mathrm{m})]} = 533\,\mathrm{sec} = 8.9\,\mathrm{min}$$ **Equation B-5**

B.2.1.2 PALLET FIRE HEAT RELEASE RATE

Wooden pallets are common in many facilities and can produce a high HRR. A correlation to estimate the HRR is in SFPE (2008) Section 1, Chapter 3, Heat Release Rates. The energy release rate from a stack of wood pallets is:

$$\dot{q}'' = 919(1+2.14h_p)(1-0.03M)$$ **Equation B-6**

Where:

$\dot{q}''$ is the HRR per unit area (kW/m^2)

h_p is the pallet stack height (m)

M is the wood moisture content (percent)

This equation is valid for stacks which are higher than 0.5 m. Below this height the equation over predicts the burning rate. It is based on a heat of combustion of 12,000 kJ/kg.

Example: For a 0.6 m high pallet stack with a nominal area of 1.2 x 1.2 m (e.g., a 5 pallet stack of typical 4 ft by 4 ft wooden drum pallets, 4.75 in. height from 5/8 in. top and bottom decking plus 3.5 in. forktine opening) and a typical 10% moisture content of the wood, based on Equation B-6, the unit-area HRR is:

$$\dot{q}'' = 919\,[1 + 2.14(0.6\,\text{m})][1 - 0.03(10\%)] = 2{,}090\,\frac{\text{kW}}{\text{m}^2}$$ **Equation B-7**

The total HRR would be:

$$\dot{q} = A\,\dot{q}'' = (1.2\,\text{m})^2\left(2{,}090\,\frac{\text{kW}}{\text{m}^2}\right) = 3{,}010\,\text{kW} = 3\,\text{MW}$$ **Equation B-8**

B.2.2 FLAME HEIGHT

Determination of a fire's flame height can be helpful in order to estimate the likelihood of further propagation or structural impacts. The flame height of a fire may be predicted using Equation B-9. This represents the height of the flames above the base of the fire (SFPE, 2008).

$$H = 0.23\,\dot{Q}^{2/5} - 1.02\,D$$ **Equation B-9**

Where:

H is the flame height (m)

$\dot{Q}$ is the HRR (kW) [note: this is the same as $\dot{q}$, but from a different reference]

D is the flame diameter (m), i.e., the diameter of the burning area as described in NUREG 1805.

Example: This equation can be applied to fires reasonably approximated by a circle. For this example, the flame height for the pallet fire developed in B2.1.2 will be found.

The effective area from Equation (B-1) is:

$$D_{eff} = \sqrt{\frac{4A}{\pi}} = \sqrt{\frac{4(1.2\text{m})(1.2\text{m})}{\pi}} = 1.4\text{m}$$ **Equation B-10**

The flame height from Equation B-9 is:

$$H = 0.23(3{,}010\,\text{kW})^{2/5} - 1.02(1.4\,\text{m}) = 4.2\,\text{m}$$ **Equation B-11**

B.2.3 ENCLOSURE FIRE DYNAMICS

Fires within an enclosure, such as a glovebox or a room in a building, exhibit distinct behavior that differs from well-ventilated fires. There are two primary differences when considering an enclosure fire: interaction with the enclosure boundary and the development of an upper layer (the hot, gaseous products of the fire that collect in the compartment.). In both cases, the enclosure boundary and the upper layer have the ability to reflect and radiate heat within the enclosure. Heat and mass transfer effects out of the boundary may also affect the behavior of the fire.

Flashover is a phenomenon of importance when analyzing enclosure fires. Flashover is "the rapid transition to a state of total surface involvement in a fire of combustible materials within an enclosure" (ASTM E176). The occurrence of flashover is dependent on many variables such as available vent area, heat transfer from the enclosure boundary, and HRR of the fire. Flashover occurs when the temperature of the enclosure, with consideration given to the radiative effects of the upper layer, is sufficient to ignite, effectively, all combustibles in the enclosure. Upon transition to flashover, the fire is in a ventilation-limited state.

PREFLASHOVER

Pre-flashover room temperatures can be estimated for simple geometries using energy balance techniques. The SFPE Fire Protection Handbook, Section 3, Chapter 6 (SFPE, 2008) describes methods that can be applied to

- Small to medium size rooms with a single open door or window; or
- Small to medium size room with forced ventilation.

The following analytical method predicts the temperature of the upper layer as a function of time. This methodology can be used to estimate the onset of flashover and can also be used as input to sprinkler or heat detector activation.

Example: Room Fire with Forced Ventilation. A 500 kW fire occurs in a ventilated steel box. The box is 2.4 m wide, 6.0 m long, and 2.3 m high with 16mm thick walls. The ventilation flow rate is 1,000 cfm (0.57 kg/s for air at standard temperature and pressure). Predict the upper layer temperature at 5.0 minutes.

The upper layer temperature is (SFPE, 2008):

$$T_g = \frac{\dot{Q}}{\dot{m}_g c_p + h_k A_T} + T_\infty \qquad \textbf{Equation B-12}$$

Where:

T_g is the upper layer gas temperature (K)

T_∞ is the ambient air temperature (K)

$\dot{Q}$ is the HRR of the fire (kW)

$\dot{m}_g$ is the ventilation mass flow (kg/s)

c_p is the specific heat of air (kJ/kg·K)

h_k is the effective heat transfer coefficient (kW/m·K)

A_T is the compartment surface area (m^2)

The compartment surface area is:

$$A_T = 2(2.3\,\text{m})[(6.0\,\text{m}) + (2.4\,\text{m})] + 2(6.0\,\text{m})(2.4\,\text{m}) = 67\,\text{m}^2$$ **Equation B-13**

The effective heat transfer coefficient for a thin-walled compartment will range from 0.012 to 0.03 $kW/m^2 \cdot K$, calculated from the following (SFPE, 2008):

$$h_k = 30 - 18\left[1 - e^{\left(-\frac{50t}{\rho\delta c}\right)}\right]$$ **Equation B-14**

Where:

h_k is the heat transfer coefficient [$W/m^2 \cdot K$]

t is the exposure time (seconds)

ρ is the compartment boundary density (kg/m^3)

δ is the compartment boundary thickness (m)

c is the specific heat of compartment boundary (J/kg·K)

Using commonly available material properties for steel, at 5 minutes (300 seconds) the effective heat transfer coefficient is:

$$h_k = 30 - 18\left[1 - e^{\left(-\frac{\left(50\frac{W}{m^2 \cdot K}\right)(300s)}{\left(7833\frac{kg}{m^3}\right)(0.0016m)\left(465\frac{J}{kg \cdot K}\right)}\right)}\right] = 13.4\frac{W}{m^2 \cdot K}$$ **Equation B-15**

The upper layer temperature is:

$$T_g = \frac{500\,\text{kW}}{\left(0.57\frac{\text{kg}}{\text{s}}\right)\left(1.01\frac{\text{kJ}}{\text{kg}\cdot\text{K}}\right)+\left(0.0134\frac{\text{kW}}{\text{m}^2\cdot\text{K}}\right)\left(67\,\text{m}^2\right)} + 293K = 632K = 360°\text{C}$$ **Equation B-16**

FLASHOVER

Upper layer temperatures, such as those found using methods discussed above, can be used to predict flashover. Upper layer temperatures of 500°C to 600°C are widely considered to be associated with the onset of flashover (SFPE 2008). More rigorous flashover prediction can be performed using methods from NFPA 555, *Guide on Methods for Evaluating Potential for Room Flashover.*

A common screening criterion for predicting flashover in a compartment with a single vent opening is detailed in the example below (NFPA 555). This example estimates the HRR necessary to achieve flashover; this can be compared to the HRR for the design fire as found using methods such as those presented in 3.2.4.1.

Example: Estimate the HRR required to cause flashover in a room 2.4 m deep, 6.0 m long, and 2.3 m high. The door is 2.36 m high and 1.19 m wide.

$$Q = 7.8\,A_{room} + 378\,A_{vent}\sqrt{H_{vent}}$$ **Equation B-17**

Where:

Q is the HRR required for flashover (kW)

A_{room} is the total area of walls, floor and ceiling, less the vent area (m^2)

A_{vent} is the total vent area (m^2)

H_{vvent} is the height of vent (m)

The vent area associated with the door would be:

$$A_V = (2.36\,\text{m})(1.19\,\text{m}) = 2.81\,\text{m}^2$$ **Equation B-18**

The surface area of the compartment would be:

$$A_T = 2(6.0\,\text{m})(2.4\,\text{m}) + (2.3\,\text{m})[2(6.0\,\text{m}) + 2(2.4\,\text{m})] - (2.81\,\text{m}^2) = 64.6\,\text{m}^2$$ **Equation B-19**

The HRR needed to create flashover with the door fully open is:

$$Q = 7.8\left(64.6\,\mathrm{m}^2\right) + 378\left(2.81\,\mathrm{m}^2\right)\sqrt{\left(2.36\,\mathrm{m}\right)} = 2{,}100\,\mathrm{kW}$$ **Equation B-20**

B.2.5 SOLID FUEL IGNITION AND RADIANT HEATING

Describing the progression of a design fire requires analysis of potential propagation. Specifically, co-located combustible materials can be ignited by a fire; determining if these combustibles will ignite in a given fire or determining the minimum separation distance to prevent ignition can be useful.

There are two basic ignition metrics: heat flux and surface temperature. Both metrics may be used, but heat flux is the more common method to predict solid fuel ignition. There are multiple test methods be used to measure ignition heat flux. Results will vary with the test method. In general ignition heat fluxes will be lower for piloted tests than for autoignition tests (piloted tests include a flame or spark; autoignition tests do not). Ignition fluxes will also vary with the duration of the exposure. Lower fluxes require longer exposures to cause ignition. A commonly accepted default ignition flux used for cellulosic materials is 12.5 kW/m^2. For additional ignition flux data see the *Ignition Handbook* (Babrauskas, 2003).

The methodology presented below estimates the heat flux imposed on a target.

NFPA 555 provides a methodology to estimate the heat flux imposed on a target:

$$\dot{q}'' = F_{f-t} E_f$$ **Equation B-21**

Where:

$\dot{q}''$ is the heat flux at the target fuel package (kW/m^2)

$F_{f\text{-}t}$ is the view factor between the flames and a differential area on the target fuel package (unitless)

E_f is the emissive power of the flames (kW/m^2)

When using the flame height estimation in equation B-9, the corresponding emissive power correlation is (NFPA 555):

$$E_f = 58\left(10^{-0.00823D}\right)$$ **Equation B-22**

Where:

E_f is the emissive power of the fire (kW/m^2)

D is the fire diameter (m)

Figure 3.2-3 shows the view factor for a differential planar element (dA_1) of an object at a specified distance (h) to a finite-length right circular cylinder, where the normal to the element passes through the

one end of the cylinder and is perpendicular to the cylinder axis. The view factor (F) is calculated as follows (Siegel & Howell, 1981):

$$F = \frac{1}{\pi H}\tan^{-1}\left(\frac{L}{\sqrt{H^2-1}}\right) + \frac{L}{\pi}\left(\frac{(X-2H)}{H\sqrt{XY}}\right)\tan^{-1}\left(\sqrt{\frac{X(H-1)}{Y(H+1)}}\right) - \frac{1}{H}\tan^{-1}\left(\sqrt{\frac{(H-1)}{(H+1)}}\right) \quad \textbf{Equation B-23}$$

Where:

F	is the view factor
h	is distance from the object to the centerline of the cylinder
l	is the height of the cylinder
r	is the radius of the cylinder
H	is the distance from the object to cylinder diameter ratio (h/r)
L	is the cylinder height to diameter ratio (l/r)
X	$(1+H)^2+L^2$
Y	$(1-H)^2+L^2$

Since the above solution is for a right cylinder with the differential area at the base of the cylinder (i.e., fire), to obtain the peak heat flux, which occurs at the mid-height of the cylinder, the actual view factor is twice the value calculated using Equation B-23, if the cylinder height is taken as half the fire height.

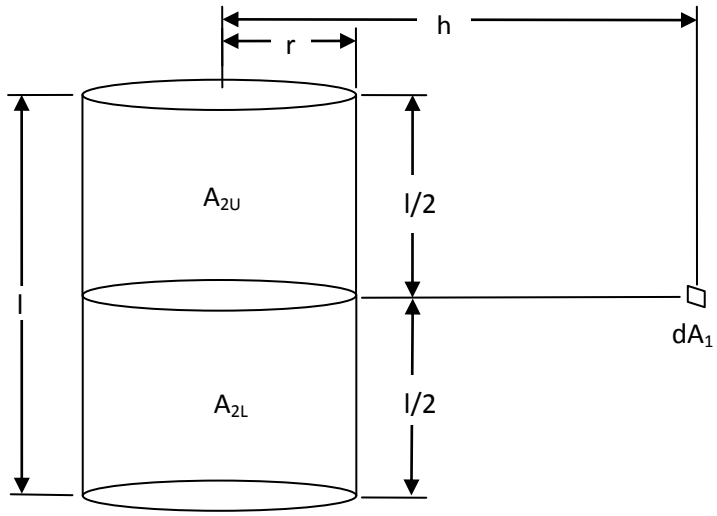


Figure B-3. Adaptation of view factor geometry for a fire model.

Example: For a 2 MW fire with a base diameter of 1.2 meters, estimate the heat flux 0.5 meters from the fire at the mid-height of the flames.

The emissive power from Equation B-22 would be:

$$E_f = 58\left(10^{-0.00823D}\right) = 57\frac{kW}{m^2}$$ **Equation B-24**

From Equation B-9 the flame height would be:

$$H = 0.235(2{,}000kW)^{2/5} - 1.02(1.2m) = 3.69m$$ **Equation B-25**

The view factor for a fire to object separation of 0.5 m is presented below:

l = 3.69 m/2 m=1.845 m

r = 1.2 m/2 m=0.6 m

h =0.5 m + 0.6 m = 1.1 m

H = h/r = 1.1 m/0.6 m = 1.833 m

L = l/r = 1.845 m/0.6 m = 3.075 m

$X = (1+H)^2+L^2 = (1+1.833)^2+(3.075)^2 = 17.48$

$$Y = (1-H)^2 + L^2 = (1-1.833)^2 + (3.075)^2 = 10.15$$

$$F = \frac{\tan^{-1}\left(\frac{3.075}{\sqrt{(1.833)^2 - 1}}\right)}{\pi(1.833)} + \frac{3.075}{\pi}\left(\frac{((17.48) - 2(1.833))}{(1.833)\sqrt{17.48(10.15)}}\right)\tan^{-1}\left(\sqrt{\frac{(17.48)((1.833)-1)}{(10.15)((1.833)+1)}}\right) - \frac{\tan^{-1}\left(\sqrt{\frac{((1.833)-1)}{((1.833)+1)}}\right)}{1.833}$$

$$= 0.26$$

As discussed previously this view factor is for a half-cylinder. The effective view factor is thus twice this value, 0.52. The heat flux would thus be:

$$\dot{q}'' = (0.52)\left(57\frac{\text{kW}}{\text{m}^2}\right) = 30\frac{\text{kW}}{\text{m}^2}$$ **Equation B-26**

B.3 WILDLAND FIRE EVENT DESCRIPTION AND ANALYSIS

Section 4.6.8, Wildland Fire Events, summarizes the approach to evaluating wildfires (also called wildland or range fires). Range fires may be caused by various natural and human initiators. These initiators include lightning, human action, mechanical incidents, and an explosion and/or fire at an off-site facility. Lightning can occur any time of the year, however it is primarily a spring and summertime phenomenon. Human action-caused incidents include improper disposal of smoking materials, poor control of a campfire, ignition by tracer fire during training, ignition by explosives during training, carelessness, and arson. Mechanical incidents include sparks generated from railways and passing automobiles.

Expected wildland fire intensity may be determined by characterizing the material available for combustion, such as trees, grasses, forbs (weeds), and low shrubs. Vegetation types are to be identified within the outlying areas, such as marshland, woodland, shrubland, and grassland. Other vegetation types may be located in small isolated pockets. The average plant production in terms of kilograms per hectare or tons/acre should be estimated.

In the bounding scenario, a wildland fire would burn the entire area surrounding a site and facilities within it and would damage facilities within the Industrial Area that are susceptible (e.g., combustible trailers/portable structures, buildings without fire resistant roofs). Smoke may necessitate site evacuation, road closures, and reconfiguration of building ventilation systems. In general, wildland fires are of such an extent, and unpredictable nature, that multiple buildings/facilities will likely be threatened, requiring fire department and other firefighting resources to be deployed accordingly. Therefore, it is typically unreasonable to assume that fire departments can respond within a specified period of time to all facilities threatened by a wildland fire. (Generally, fire department response during wildland fires is addressed in the Fire Protection and Emergency Management programs in accordance with the guidance of DOE-STD-1066, *Fire Protection*, Appendix F, paragraph 6.1.4.)

Wildland fire analysis for DSA hazard evaluations and accident analysis at nuclear facilities should be closely coupled to the Facility FHA in accordance with DOE-STD-1066. NFPA 1144, *Standard for Reducing Structure Ignition Hazards from Wildland Fire*, 2013 Edition, provides valuable standardized guidance for the analysis of the susceptibleness of a structure to wildland fires. The NFPA standard

identifies the key elements of the structure and the surrounding environment that require evaluation. These key elements in turn, contribute to the safety analyst's understanding and selection of controls for the mitigated analysis.

Table B-1 is based on an example hazard assessment from Table A.4.1.2 of NFPA 1144, "Example of Structure Assessment Rating Form." The five areas of evaluation are:

- Overview of the surrounding environment – topography, weather, and surrounding structures;
- Chimney to eaves – roof construction, skylights, and roof attachments;
- Top of exterior wall to foundation – wall construction, openings and penetrations;
- Foundation to Immediate Landscaped Area (ILA) – vegetative fuels and other combustibles around the structure, heat and flame sources, other structures and vehicle parking within 30 ft;
- ILA to the extent of the Structure Ignition Zone (SIZ) – vegetation, heat and flame sources, and vehicle parking between the outer edge of the ILA and the extent of the SIZ.

This assessment should typically be performed in coordination with a designated Fire Protection Engineer and included in the facility Fire Hazard Analysis (FHA). As seen in Table B-1, the results provide four hazard ratings that can be used to aid in assessing the probability of a wildland fire causing a release of facility MAR. The evaluation areas also aid in identifying existing passive design features that may be credited in the safety basis or may need to be improved to provide the necessary protection of facility MAR. The table may be used to perform iterative analysis as well since it identifies controls (e.g. vegetation control/treatment within the Structure Ignition Zone). This Handbook provides some amplifying information to the NFPA 1144 table (highlighted in yellow) for use by safety analysts in the DSA development/revision process. Annex A of NFPA 1144 provides additional detailed explanatory information.

Building design, location and construction standards that reduce structural susceptibility to wildland fires are provided in Chapter 5 of NFPA 1144 and NFPA 1141, *Standard for Fire Protection Infrastructure for Land Development in Wildland, Rural, and Suburban Areas*, as well as local building codes. Section 4.2.5.8 of NFPA 1144 states, "Any structure that fails to comply with the requirements of Chapter 5 shall be deemed to increase the risk of the spread of wildland fire to improved property and the risk of fires on improved property spreading to wildland fuels."

Some additional sources of guidance for fire hazards analysis, building design and construction, exterior exposure protection, and wildland fire management include the following:

- DOE-STD-1066-2012, *Fire Protection*, was developed to address the special or unique fire protection issues at DOE facilities and includes guidance (and additional references) for wildland fire management and facility design against wildland fire exposures. Specifically, Chapter 7 and Appendix B address the Fire Hazard Analysis which includes wildland fire exposure.
- NFPA 801, *Fire Protection for Facilities Handling Radioactive Materials*, addresses fire protection requirements intended to reduce the risk of fires and explosions at facilities handling radioactive materials. NFPA 801, Section 5.5 specifically states, "Buildings in which radioactive materials are to be used, handled, or stored shall be fire-resistant or noncombustible construction in accordance with NFPA 220, *Standard on Types of Building Construction*, Type I or Type II construction."

- NFPA 80A, *Recommended Practice for Protection of Buildings from Exterior Fire Exposures*, provides guidance on fire exposure hazards. NFPA 80A , Chapter 4 provides guidance for determining minimum building separation distances, and Chapter 5 identifies various means by which facilities may be protected from fire damage due to exterior exposure.
- NFPA 1143, *Standard for Wildland Fire Management*, provides guidance that aids in the development of wildland fire management programs, which include the full range of activities and functions necessary to plan, prepare, and respond to potential fires.

Definitions:

- Immediate Landscaped Area (ILA): This area, often referred to as the "defensible space" between an improved property and a potential wildland fire, is a zone extending at least 30 ft from the foundation of the structure, including the footprint of decks and all extensions, in which vegetation has been modified for reduced flammability or aesthetic purposes.
- Structure Ignition Zone (SIZ): The "ignition zone" includes the structures and their immediate surroundings, including all vegetation that contains potential ignition source and fuels that can affect ignition potential during an intense Wildland fire. The zone extends 0–200 ft (0–60 m) out from a structure's foundation.

Table B-1. Wildland Fire Facility/Structure Hazard Analysis Based on NFPA 1144

Analyzed Parameters	**Environment**	**Building Structure**		**Landscape/Combustibles**	
Rating Values by Areas Assessed	Overview of Surrounding Environment (4.2.1*)	From Chimney to Eaves (4.2.2*)	From Top of Exterior Wall to Foundation (4.2.3*)	From Foundation to ILA (0 to 30 ft) (4.2.4*)	From ILA to Extent of SIZ (30 to 200 ft) (4.2.5*)
Topographical Features					
1. Topographical features that adversely affect wildland fire behavior (4.2.1*)	(0-5)				
2. Areas with history of high fire occurrence (4.3.4*)	(0-5)				
3. Areas exposed to unusually severe fire weather and strong, dry winds (4.2.1.3*)	(0-5)				
4. Local weather conditions and prevailing winds (4.2.1.2*)	(0-5)				
5. Separation of structures on adjacent property that can contribute to fire spread/behavior (4.2.1.3*)	(0-5)			(0-5)	(0-5)
Vegetation—Characteristics of predominant vegetation					
1. Light (e.g. grasses, forbs, sawgrasses, and tundra)	5			15	5

Analyzed Parameters	**Environment**	**Building Structure**		**Landscape/Combustibles**	
Rating Values by Areas Assessed	Overview of Surrounding Environment (4.2.1*)	From Chimney to Eaves (4.2.2*)	From Top of Exterior Wall to Foundation (4.2.3*)	From Foundation to ILA (0 to 30 ft) (4.2.4*)	From ILA to Extent of SIZ (30 to 200 ft) (4.2.5*)
2. Medium (e.g. light brush and small trees) NFDRS Fuel Models D, E, F, H, P, Q, and U	10			20	5
3. Heavy (e.g. dense brush, timber, and hardwoods) NFDRS Fuel Models B, G, and O	15			25	15
4. Slash (e.g. timber harvesting residue) NFRDS Fuel Models J, K, and L	15			30	20
Topography (4.2.1.1, 4.2.4, 4.2.5*)					
1. Slope 5-9%				1	1
2. Slope 10-20%				4	2
3. Slope 21-30%				7	3
4. Slope 31-40%				10	6
5. Slope >41%				15	10
Building Setback, relative to slopes of ≥ 30% (4.2.1.5, 5.1.3.2*)					
1. ≥30 ft (9.14 m) to slope	1				
2. <30 ft (9.14 m) to slope	5				
Roofing Materials and Assembly, nonrated** (4.2.2.1, 4.2.2.3*)		50†			
Ventilation Soffits, without metal mesh or screening (4.2.3.4*)		20			
Gutters, combustible (4.2.2.4, 4.2.2.5*)		5			
Building Construction (predominant) **(4.2.4*)**					
1. Siding and Deck—noncombustible/fire-resistive/ignition-resistant			Low†† (0 - 10)		
2. Siding—noncombustible/fire-resistive/ignition-resistant siding, but Deck—combustible			Medium†† (10 - 15)		
3. Siding and Deck—combustible			High†† (15)		

Analyzed Parameters	Environment	Building Structure		Landscape/Combustibles	
Rating Values by Areas Assessed	Overview of Surrounding Environment (4.2.1*)	From Chimney to Eaves (4.2.2*)	From Top of Exterior Wall to Foundation (4.2.3*)	From Foundation to ILA (0 to 30 ft) (4.2.4*)	From ILA to Extent of SIZ (30 to 200 ft) (4.2.5*)
Fire resistance of wall components (e.g. doors, windows, and penetrations) are also considered in the building construction evaluation. Value above for item 1 may increase up to 10 based on extent of vulnerabilities created in the walls. Likewise the value of item 2 may increase up to 15 due to vulnerabilities.					
Fences and Attachments **(4.2.4.3*)**					
Combustible				15	
Non-combustible				0	
Placement of Gas and Electric Utilities					
One underground, one aboveground	3				
Both aboveground	5				
Both underground	0				
Fuel Modifications within structure ignition zone **(4.2.4, 4.2.5*)**					
71-100 ft (21-30 m) of vegetation treatment from the structure(s)					5
30-70 ft (9-21 m) of vegetation treatment from the structure(s)				7	
<30 ft (9 m) of vegetation treatment from the structure(s)				15	
Note: Evaluate the presence and location of heat sources, flame sources and vehicle parking from the foundation to the ILA (4.2.4.2 and 4.2.4.5*) and throughout the SIZ (4.2.5.3 and 4.2.5.5*). For example, even with no vegetation in the Defensible Space (<30 ft), the presence of fuel, heat and flame sources (e.g. propane tanks, parked vehicles, combustible waste containers) could be sufficient cause to result in a high evaluation value of 15.					
Fixed Fire Protection (NFPA 13, 13R, or 13D sprinkler system(s))					
No Protection			5		
Protected			0		
TOTALS					
Hazard Rating Scale (Total the above individual ratings and compare the totals to scale below.) Estimated Structure Ignition Hazard from Wildland Fire: (F is estimated probability of structure ignition for input into DSA.)					
Slight	0-14	0-14	0-14	0-14	0-14
Moderate	15-29	15-29	15-29	15-29	15-29
Significant	30-49	30-49	30-49	30-49	30-49
Severe	≥50	≥50	≥50	≥50	≥50
Note: The estimated probability of structure ignition is intended as a guide to be used to aid in determining scenario/event frequency in the DSA hazard analysis. Each of the individual columns (areas of evaluation) above assess a group of features/controls that reduces the likelihood that a wildland fire will breach the facility external					

Analyzed Parameters	Environment	Building Structure		Landscape/Combustibles	
Rating Values by Areas Assessed	Overview of Surrounding Environment (4.2.1*)	From Chimney to Eaves (4.2.2*)	From Top of Exterior Wall to Foundation (4.2.3*)	From Foundation to ILA (0 to 30 ft) (4.2.4*)	From ILA to Extent of SIZ (30 to 200 ft) (4.2.5*)
structure. The likelihood that the structure will be breached by the wildland fire is determined primarily by the most vulnerable feature (highest column value). The recommended probability input to the DSA HA is the probability value associated with the most severe hazard rating identified.					

B.3.1 EXAMPLE OF THE APPLICATION OF THE WILDLAND FIRE FACILITY/STRUCTURE HAZARD ANALYSIS

A simple example of the application of the Wildland Fire Facility/Structure Hazard Analysis presented in Table B-2 is provided below. For this example, the most significant characteristics of the facility are listed below. However, for specific facilities, additional detailed information should also be available.

- The facility location is in a semi-arid region that may be subjected to significant straight winds;
- The region has a history of wildland fires (about 1 every 10 years);
- The surrounding environment is timberland (mostly ponderosa pine) and grassland;
- Large trees have been removed and the brush is thinned out to a distance of 205 to 210 ft. (When properly performed, this fuel modification treatment significantly reduces the flame and radiative heat threat to the structure from the SIZ, as shown in this example under the section for Fuel Modification within the SIZ);
- A controlled defensible space is provided for a minimum of 30 ft from the foundation of the structure in all directions;
- The nearest sloping grade of greater than 10% is more than 400 ft from facility;
- Although the concrete structure of the walls are 1 to 2 hour fire resistance capable, penetration seals in several concrete walls are not fire-rated, resulting in fire resistance vulnerabilities in the walls;
- The facility roof has been evaluated by fire protection engineering and is considered to meet UL Class A/FM Class 1 requirements;
- There are no skylights in the roof;
- Existing gutters are constructed of metal;
- Some ventilation fan suction and discharge duct external openings are not covered by metal screening;
- Vehicles are parked within the SIZ on paved parking lots clear of vegetation. The facility is equipped with a dock for equipment and material shipping and receiving. No vehicles are parked or left unattended within 30 ft of the facility;
- A neighboring structure is a single story transportable building of combustible materials with an attached wood deck with no underpinning or screening. This structure is 60 to 70 feet away; and
- No other significant combustibles are permanently located or stored within 30 ft of the facility.

Table B-2. Example Application of Wildland Fire Facility/Structure Hazard Analysis

Analyzed Parameters	**Environment**	**Building Structure**		**Landscape/Combustibles**	
Rating Values by Areas Assessed	Overview of Surrounding Environment (4.2.1*)	From Chimney to Eaves (4.2.2*)	From Top of Exterior Wall to Foundation (4.2.3*)	From Foundation to ILA (0 to 30 ft) (4.2.4*)	From ILA to Extent of SIZ (30 to 200 ft) (4.2.5*)
Topographical Features					
1. Topographical features that adversely affect wildland fire behavior (4.2.1*)	2				
2. Areas with history of high fire occurrence (4.3.4*)	4				
3. Areas exposed to unusually severe fire weather and strong, dry winds (4.2.1.3*)	5				
4. Local weather conditions and prevailing winds (4.2.1.2*)	4				
5. Separation of structures on adjacent property that can contribute to fire spread/behavior (4.2.1.3*)	3			4	4
Vegetation—Characteristics of predominant vegetation					
1. Light (e.g. grasses, forbs, sawgrasses, and tundra)	5			15	
2. Medium (e.g. light brush and small trees) NFDRS Fuel Models D, E, F, H, P, Q, and U					5 Ponderosa Pine
3. Heavy (e.g. dense brush, timber, and hardwoods) NFDRS Fuel Models B, G, and O					
4. Slash (e.g. timber harvesting residue) NFRDS Fuel Models J, K, and L					
Topography					
1. Slope 5-9%					1
2. Slope 10-20%				4	
3. Slope 21-30%					
4. Slope 31-40%					

Analyzed Parameters	Environment	Building Structure		Landscape/Combustibles	
Rating Values by Areas Assessed	Overview of Surrounding Environment (4.2.1*)	From Chimney to Eaves (4.2.2*)	From Top of Exterior Wall to Foundation (4.2.3*)	From Foundation to ILA (0 to 30 ft) (4.2.4*)	From ILA to Extent of SIZ (30 to 200 ft) (4.2.5*)
5. Slope >41%					
Building Setback, relative to slopes of ≥ 30%					
1. ≥30 ft (9.14 m) to slope					
2. <30 ft (9.14 m) to slope					
Roofing Materials and Assembly, nonrated**					
Ventilation Soffits, without metal mesh or screening		20			
Gutters, combustible					
Building Construction (predominant)					
1. Siding and Deck—noncombustible/fire-resistive/ignition-resistant					
2. Siding—noncombustible/fire-resistive/ignition-resistant siding, but Deck—combustible					
3. Siding and Deck—combustible			15		
Fire resistance of wall components (e.g. doors, windows, and penetrations) are also considered in the building construction evaluation. Value above for item 1 may increase up to 10 based on extent of vulnerabilities created in the walls. Likewise the value of item 2 may increase up to 15 due to vulnerabilities.					
Fences and Attachments					
Combustible					
Non-combustible				0	
Placement of Gas and Electric Utilities					
One underground, one aboveground	3				
Both aboveground					
Both underground					
Fuel Modifications within structure ignition zone					
71-100 ft (21-30 m) of vegetation treatment from the structure(s)					
30-70 ft (9-21 m) of vegetation treatment from the structure(s)					
<30 ft (9 m) of vegetation					

Analyzed Parameters	Environment	Building Structure		Landscape/Combustibles	
Rating Values by Areas Assessed	Overview of Surrounding Environment (4.2.1*)	From Chimney to Eaves (4.2.2*)	From Top of Exterior Wall to Foundation (4.2.3*)	From Foundation to ILA (0 to 30 ft) (4.2.4*)	From ILA to Extent of SIZ (30 to 200 ft) (4.2.5*)
treatment from the structure(s)					
Note: Evaluate the presence and location of heat sources, flame sources and vehicle parking from the foundation to the ILA (4.2.4.2 and 4.2.4.5*) and throughout the SIZ (4.2.5.3 and 4.2.5.5*). For example, even with no vegetation in the Defensible Space (<30 ft), the presence of fuel, heat and flame sources (e.g. propane tanks, parked vehicles, combustible waste containers) could be sufficient cause to result in a high evaluation value of 15.					
Fixed Fire Protection (NFPA 13, 13R, or 13D sprinkler system(s))					
No Protection					
Protected			0		
TOTALS	**26**	**20**	**15**	**23**	**10**
Hazard Rating Scale (Total the above individual ratings and compare the totals to scale below.) Estimated Structure Ignition Hazard from Wildland Fire: (F is estimated probability of structure ignition for input into DSA.)					
Slight	0-14	0-14	0-14	0-14	0-14
Moderate	15-29	15-29	15-29	15-29	15-29
Significant	30-49	30-49	30-49	30-49	30-49
Severe	≥50	≥50	≥50	≥50	≥50
Note: The estimated probability of structure ignition is intended as a guide to be used to aid in determining scenario/event frequency in the DSA hazard analysis. Each of the individual columns (areas of evaluation) above assess a group of features/controls that reduces the likelihood that a wildland fire will breach the facility external structure. The likelihood that the structure will be breached by the wildland fire is determined primarily by the most vulnerable feature (highest column value), which for this example, the estimated probability of structure ignition is Moderate. The recommended probability input to the DSA HA is the probability value associated with the most severe hazard rating identified, and is based on a qualitative judgment considering other factors.					
* Ref. NFPA 1144, 2013 Edition ** Ref. LA-UR-14-27684, Analysis of Wildland Fire Hazard to the TWF at Los Alamos National Labs, Gilbertson, Sarah Elizabeth, October 2, 2014					

The hazard rating results of Tables B-1 and B-2 for the probability that a wildland fire in the vicinity of the facility will breach the structural barrier provides input into the DSA hazards analysis likelihood determinations. Tables B-1 and B-2 should be performed for both the unmitigated (no controls) and mitigated (controls in place) cases to provide input and justification to the unmitigated and mitigated DSA hazard analysis wildland fire scenarios, respectively.

The design features and controls (engineering and administrative) that are assumed in Tables 4-8 and 4-9 for the reduction of the hazard rating are carried forward to the DSA as appropriately credited or defense-in-depth controls.

Typically, the Leak Path Factor (L) is assumed to be 1 for an unmitigated wildland fire that results in a release of MAR from a facility because the facility structural boundary is assumed to be significantly breached.

The damage ratio for the wildland fire is facility dependent, and considers the capability of other MAR containment components to withstand the fire.

The Table B-2 example documents the results of the FHA assessment of wildland fire, which should be interpreted and included in the FHA or referenced to a supporting analysis. The DSA Chapter 3 hazard evaluation or accident analysis would then summarize the analysis and reference the FHA, and expand on how the likelihood was assigned, identify and the protection features, and evaluate their safety significance.

APPENDIX C EXPLOSION ANALYSIS

This Appendix includes the following information supporting explosion analysis:

- Flammable Gas Limits Calculation
- Basic Methods for Evaluating Explosions
- Methods for Evaluating Types of Explosions, including
  - Vapor Cloud Explosions
  - Vessel Explosions
  - BLEVE
- Damage Analysis
- Example Calculations

C.1 FLAMMABLE GAS LIMITS CALCULATION

For a mixture of flammable gases, the Composite Lower Flammability Limit (CLFL) -also known as Le Chatelier's Law- is calculated:

Equation C-1

$$C_{CLFL} = \frac{1}{\frac{f_1}{LFL_1} + \frac{f_2}{LFL_2} + \ldots \frac{f_n}{LFL_n}}$$

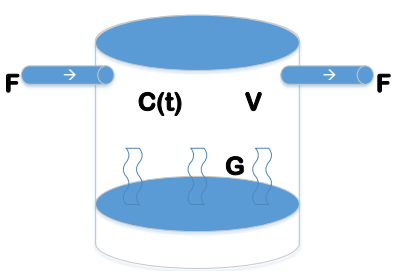
Where:

C_{CLFL} [dimensionless] – is the CLFL

f_i [dimensionless] – fraction of flammable i in the mixture

LFL_i [dimensionless] – Lower Flammability Level of component i in the mixture.

The LFL and UFL are typically provided in volume percent. Table C-1 lists the LFL for some of the most commonly found combustible gases at a temperature of 25 ^{o}C.



For flammability calculations in a closed vessel or tank, the concern is often the time available before LFL is reached. Under no ventilation conditions, the time-to-CLFL is formulated from the mass transfer differential equation:

Equation C-2

$$V\frac{dC}{dt} = G - FC$$

Where:

G [moles/hr] – flammable gas generation rate due to radiolysis or other mechanisms.

F [ft^3/hr] – Purge flow rate

C [moles/ft^3] – initial flammable concentration

Solving C-2 yields:

$$C(t) = \frac{G}{F}\left[1 - e^{-\alpha t}\right]$$ **Equation C-3**

$$\alpha = \frac{F}{V}$$

Where:

α [1/hr]– time constant

V [ft^3] – vapor space volume in the vessel or tank,

t [hr] – time

Solving the equation C-3 for time, we have;

$$T_{CLFL} = -\frac{1}{\alpha}\ln\left(1 - \frac{C \cdot F}{G}\right)$$ **Equation C-4**

In order to prevent potential combustion and subsequent explosions, a relationship of the various gases involved must be kept, at a given CLFL, below or equal to 1. Given a calculated CLFL for hydrogen and benzene an example is:

$$\frac{X_{H_2}}{LFL_{H_2}} + \frac{X_{benz}}{LFL_{benz}} = 1$$ **Equation C-5**

Where:

X_{H2} and X_{benz} are respectively the concentration of Hydrogen and Benzene in fuel/air mixture.

Limiting Case

For a given level in a waste tank with liquid and headspace volumes, the most limiting case is that the waste liquid can generate enough hydrogen such that the hydrogen concentration in the headspace just reaches the stoichiometric concentration. At stoichiometric concentration, the oxygen in the headspace is completely used for combustion. Table C-1 lists the stoichiometric concentrations of commonly found waste tank gases.

Table C-1. LFL Values for Some Types of Combustible Gases (T=25°C).*

Combustible Gas	LFL (volume percent) (T=25°C)*	LFL (volume percent) Stoichiometric Concentrations*
Hydrogen	4.0	29.5
Methane	5.0	9.48
Benzene	1.37	2.72

Combustible Gas	LFL (volume percent) (T=25°C)*	LFL (volume percent) Stoichiometric Concentrations*
Isopropanol	2.2	4.65
Methanol	6.7	12.25
Propane	1.7	4.98
Hexane	1.1	2.16
Toluene	1.1	2.27
Xylene	1.1	1.96
Isopar-L	0.66	1.22

*Additional LFLs can also be found in U.S. Bureau of Mines Bulletin 680

C.2 COMMON METHODS TO CALCULATE EXPLOSIVE EVENTS

C.2.1 TNT-EQUIVALENT METHOD

The concept of TNT-equivalency was introduced for blast prediction purposes when the mechanisms of blast generation in vapor clouds were not fully understood. The method simply converts the available combustion energy into an equivalent charge weight of TNT. Noted that the literature on this subject does not use consistent terminology, hence it is common that TNT equivalency is also called equivalency factor, yield factor, efficiency, or efficiency factor. This TNT method is for gas explosions outside of facilities (i.e., unconfined explosions). The "TNT equivalence factors" come from assessing the damage to the exterior of buildings from the gas explosion vs. the quantity of TNT to cause the same damage. This method is not valid for inside building explosions.

The conversion is accomplished using the following conversion factor:

$$W_{TNT} = \alpha_e \frac{\left(W_f H_f\right)}{H_{TNT}} = \alpha_m W_f$$ **Equation C-6**

Where:

W_{TNT} [kg] – equivalent mass of TNT or yield

W_f [kg] – the mass of fuel involved

H_f [J/kg] – heat of combustion of the fuel in question

H_{TNT} [J/kg] – heat of combustion of TNT

α_e [dimensionless] – TNT equivalency based on energy

$\alpha_m = \alpha_e (H_f / H_{TNT})$ [dimensionless] – TNT equivalency based on mass

In order to apply the TNT-equivalency model, the analyst needs to choose values of α_e, f_F (the fraction of the fuel that should be used in the calculation), H_f, and H_{TNT}. A discussion of practices for choosing these values is provided below.

α_e, TNT-Equivalency Based on Energy

For stoichiometric, hydrocarbon-air detonation, the theoretical maximum efficiency of conversion of heat of combustion into blast is approximately 40 percent (CCPS, 1994). In practice, however, the efficiency is usually less than this—for example, because vapor cloud explosions are usually deflagrations and not full detonations, or because the mixtures are not fully stoichiometric. *Unconfined Vapor Cloud Explosions* (Gugan, 1979) presents estimates of α_e from a number of accidental vapor cloud explosions: many of the estimates are considerably smaller than $\alpha e = 0.4$. Section 4.3.1 of *Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires and BLEVEs* (CCPS, 1994) provides further discussion of vapor clould explosions.

Table C-2 provides a number of references in which values of α_e have been estimated. These choices are based on EPA's review of the information in Gugan (1979). This Handbook considers the EPA guidance adequate for the purposes of accident analysis.

Table C-2. Sources for TNT Equivalency Factor Estimations.

References	**α_e**
Dow Chemical (Brasie and Simpson, 1968)	$0.02 \le \alpha_e \le 0.05$
United Kingdom Health and Safety Executive (HSE, 1979)	$\alpha_e = 0.03$
Exxon (unpublished; CCPS, 1994)	$0.03 \le \alpha_e \le 0.10$
Industrial Risk Insurers (1990)	0.02
The U.S. Environmental Protection Agency (EPA-550-B-99-009) in its guidance for explosion modeling in the context of its Risk Management Program (RMP) regulations, recommends:	
For worst-case explosion analysis	0.1
Factory Mutual Research Corp (Section 4.3.1 of CCPS, 1994)	0.05-0.15
For "alternative" or "more likely" scenarios	0.03

The Fraction of Fuel That Should Be Included in the Calculation

The value of f_F is dependent on the mode of release:

- For a catastrophic failure of a vessel containing a pressurized gas, f_F should be taken to be unity.
- For a catastrophic failure of a vessel containing a gas liquefied under pressure (such as liquid propane), the physics of the situation is more complicated. In such circumstances, some fraction V_F of the liquid flashes to vapor and the rest cools to the boiling point of the liquid (or lower). The flash fraction can be determined on the basis of actual thermodynamic data using the following equation:

$$V_F = 1 - \exp\left(\frac{C_p \Delta T}{L}\right)$$ **Equation C-7**

Where:

V_F [dimensionless] – Flash Fraction

C_p [kJ/kg/K] – mean specific heat of the flashing material at constant pressure

ΔT [K] – difference in temperature between the temperature of the vessel and the atmospheric boiling point

L [kJ/kg] – latent heat of vaporization

Some of the liquid is fragmented into droplets, some of which may remain airborne. The amount of droplets that become and remain airborne are functions of the difference between the temperature of the liquid in the vessel and its atmospheric boiling point (the superheat). The phenomenology of this process is not completely understood. However, CCPS, 1994, based on work by the UK HSE, recommends that the flash fraction be determined on the basis of actual thermodynamic data as above and should be doubled to allow for aerosol formation ($f_F = 2\ V_F$ subject to the upper limit $f_F = 1$).

For other than catastrophic releases (such as a jet release from a vessel containing a gas under pressure or a gas liquefied under pressure, where the release approximates a steady state), it is in principle possible to use an atmospheric dispersion model to determine the amount of fuel at any one time that lies between the upper and lower flammable limits. For a prolonged release, this amount is a small fraction of the total amount released (i.e., $f_F << 1$) and using the full amount released would be excessively conservative.

Calculation of Distance to Given Overpressure

Once W_{TNT} has been determined, the "scale distance" can be calculated by the following simple expression:

$$\text{Scaled Distance} = \frac{\text{Actual Distance}}{\sqrt[3]{W_{TNT}}} \quad [\text{ m.kg}^{1/3}\text{]}$$

Equation C-8

This equation has been plotted in Figure C-1, from where the side overpressure can be read on the vertical axis. There are, however, certain caveats. TNT blast is a poor model for a gas explosion blast. In particular, the positive phase duration and shape of the blast waves is not well reproduced. However, TNT-equivalency methods are satisfactory, so long as far-field potential damage is the concern.

C.2.2 THE MULTI-ENERGY METHOD (VAN DEN BERG 1985)

The basic tool for the application of the Multi-Energy model is based on a set of scaling equations also known as Sach's scaling equations: Additional information on the Multi-Energy Method can be found in Section 4.3.2 of CCPS (1994) and Sections 4.8.4 to 4.8.9 of *Estimating the Flammable Mass of a Vapor Cloud* (CCPS, 1999b).

The scaling equations are:

$$R_S = \frac{R}{\sqrt[3]{\frac{E}{p_0}}}\ ;$$

Equation C-9

$$\Delta P_S = \frac{\Delta P}{p_0}$$

Equation C-10

Equation C-11

$$t_{+S} = \frac{t_{+} \cdot c_0}{\sqrt[3]{\frac{E}{p_0}}}$$

Where:

R_s [dimensionless] – energy scaled distance

R [m] – actual distance from source of explosion

E [J] – charge combustion energy

p_0 [Pa] – ambient pressure

ΔP_s [dimensionless] – maximum side-on overpressure

ΔP [Pa] – side-on blast overpressure

t_{+s} [dimensionless] – positive-phase duration as a function of the combustion

t_{+} [s] – the positive-phase duration

c_0 [m/s] – ambient speed of sound

Once calculated, a number ranging from 1 (very low strength) up to 10 (detonative strength) represents initial blast strength in Figure C-1 and Figure C-2. In addition, Figure C-1 and Figure C-2 give a rough indication of the blast-wave shape, which corresponds to the characteristic behavior of a gas-explosion blast. A summary of the necessary steps to apply the method with the needed calculations is seen in the next Figure C-3.

The analysts can find a comprehensive introduction to the Multi-Energy model in “BLAST – A 1-D Variable Flame Speed Blast Simulation Code Using a ‘Flux-Corrected Transport’ Algorithm,” (Van den Berg, 1980).

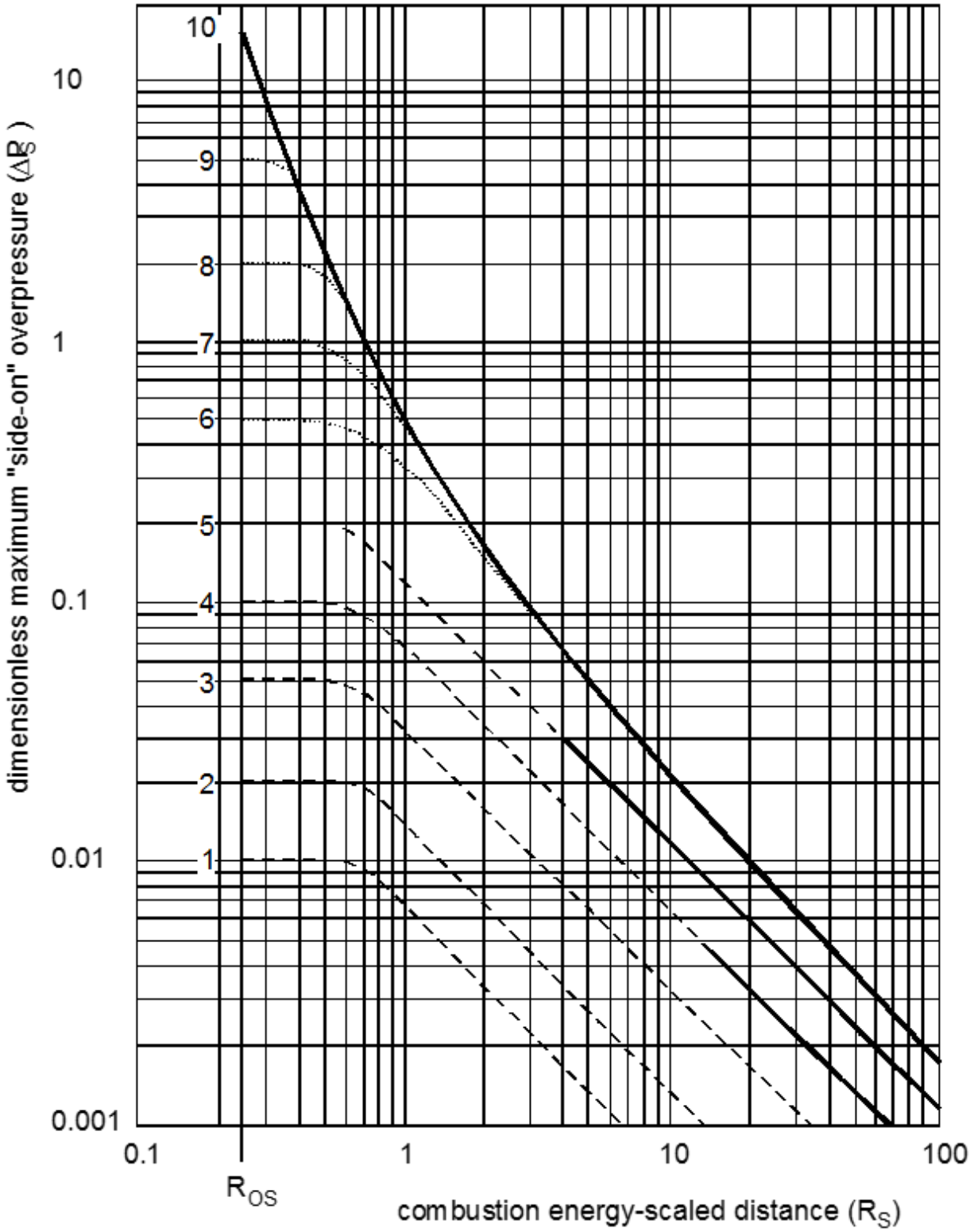


Figure C-1. Sachs-Scaled Side-on Peak Overpressure of Blast from a Hemispherical Fuel-Air Charge.

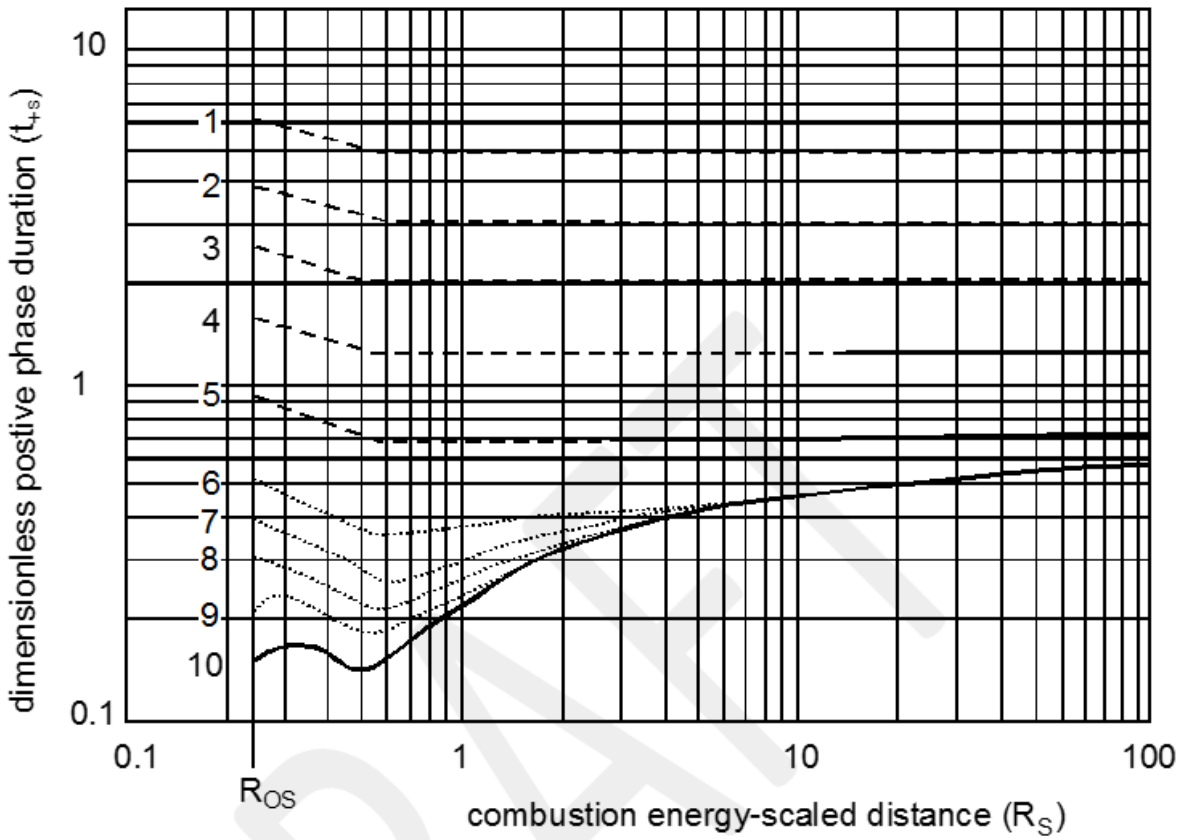


Figure C-2. Sachs-Scaled Positive-Phase Duration of Blast from a Hemispherical Fuel-Air Charge.

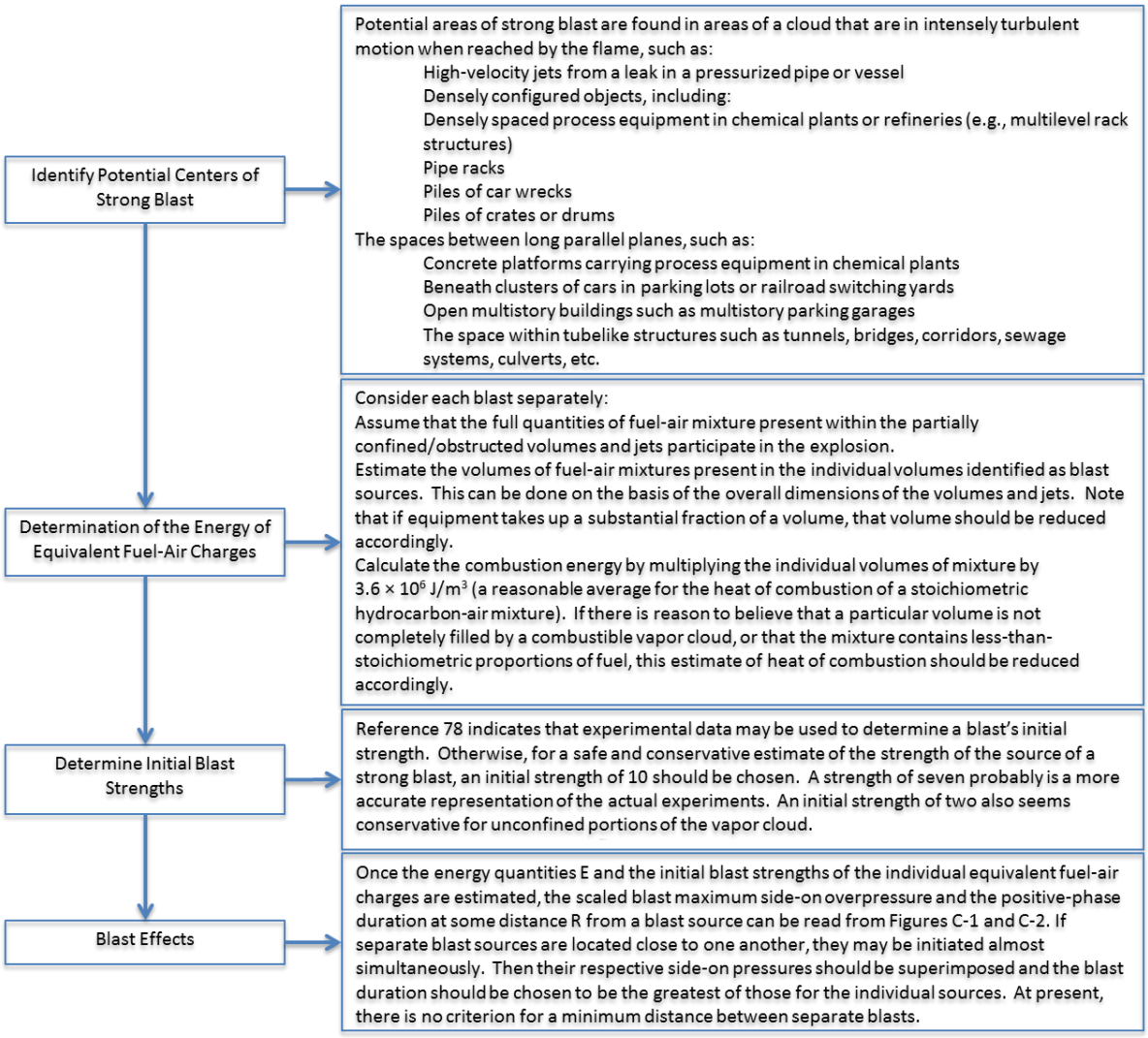


Figure C-3. Multi-energy Calculation Method Steps.

C.2.3 MORE SOPHISTICATED MODELS

The models presented above are relatively simple. The drawback is that the simplifying assumptions sometimes do not reflect reality. Often, for example, the blast effects are not symmetrical. The above models do not give a profile of side-on overpressure as a function of time at a specific point. Such information may well be needed if the objective is to provide design information for a building. In such circumstances, a numerical simulation model may be needed (CCPS, 1994).

C.3 ANALYSIS OF SPECIFIC TYPES OF EXPLOSIONS

C.3.1 VAPOR CLOUD EXPLOSION

The difference between a blast effect and a flash fire is given by the presence of the following conditions:

1. partial confinement and/or obstruction
2. jet release
3. explosively dispersed cloud
4. high-energy ignition source.

If the above conditions are not present, then a flash fire is said to occur.

Flame height

A basic formula for flame height H when a vapor cloud ignites is given by the following empirically derived equation (CCPS, 1994):

Equation C-12

$$H = 20D \cdot \sqrt[3]{\left(\frac{v_f^2}{gd}\right)\left(\frac{\rho_0}{\rho_a}\right)^2\left(\frac{w\alpha r^2}{(1-w)^3}\right)}$$

where:

H [m] – visible flame height

D [m] – cloud depth

$v_f = 2.3\ U_w$ [m/s] – flame speed

U_w [m/s] – windspeed

g [m/s^2] – acceleration due to gravity

d [m] – radius of the cloud from the explosion center

ρ_0 [kg/m^3] – density of fuel-air mixture

ρ_a [kg/m^3] – density of air

α [dimensionless] – expansion ratio for stoichiometric combustion under constant pressure (typically 8 for hydrocarbons)

$w = (\Phi - \Phi_{st})/[\alpha(1 - \Phi_{st}]$ for $\Phi > \Phi_{st}$

$w = 0$ for $\Phi \leq \Phi_{st}$

$r = (1 - \Phi_{st})M_{air}/\Phi_{st}M_{fuel}$ [dimensionless] – stoichiometric fuel-air mass ratio

Φ [dimensionless] – fuel-air mixture composition (fuel volume ratio)

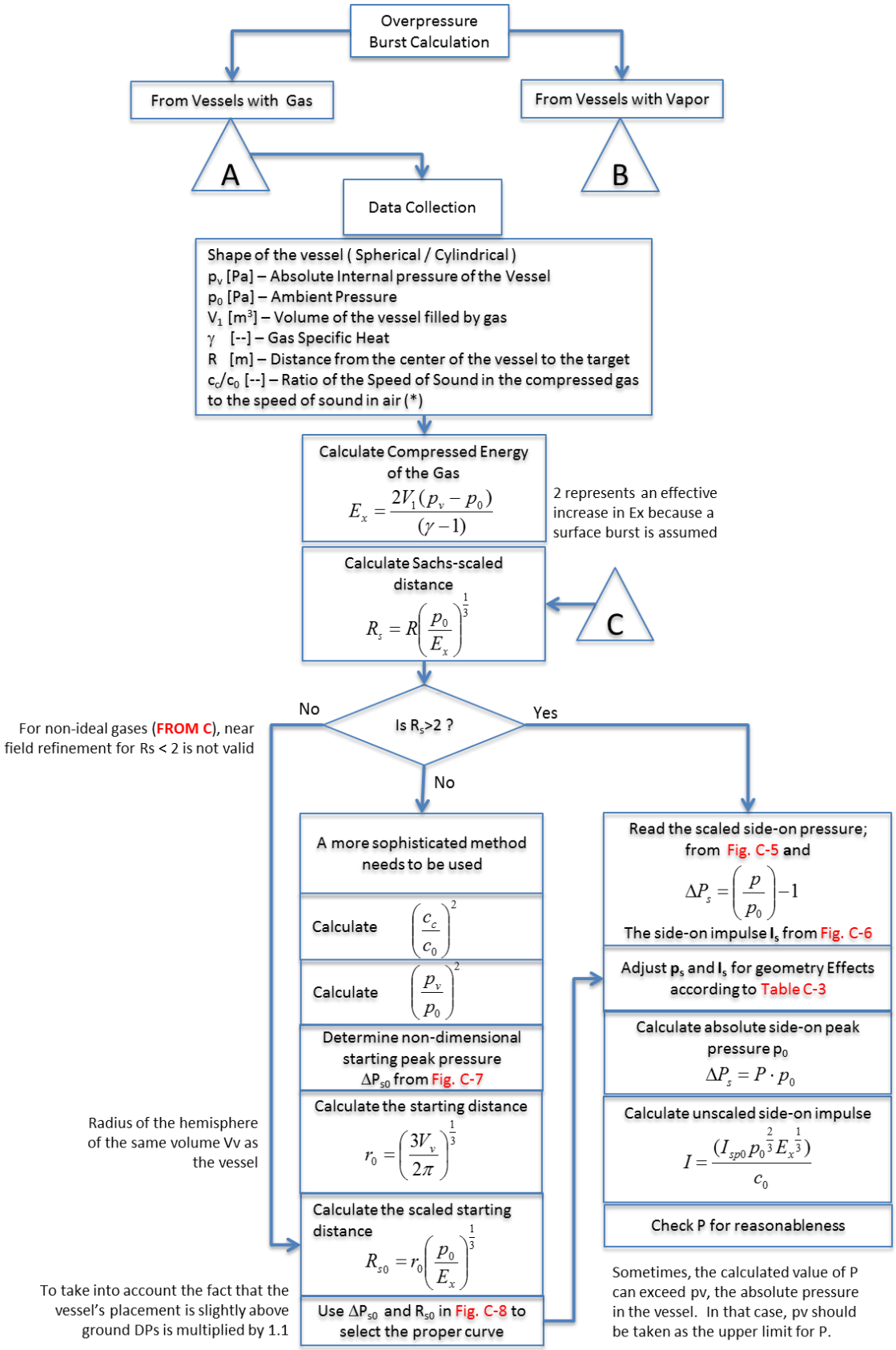
Φ_{st} [dimensionless] – stoichiometric mixture composition (fuel volume ratio)

M_{air} [kg] – mass of air in vapor cloud

M_{fuel} [kg] – mass of fuel in vapor cloud

C.3.2 Blast Effect from Vessels

The following Figure C-4 depict the relevant steps used to calculate blast explosion effects from vessels filled with gases that can reasonably be approximated as ideal (path under A) and from vessels filled with non-ideal fluids or with superheated liquids (path under B) (Baker, et. al., 1977; CCPS, 1994)


Overpressure Burst Calculation
From Vessels with Gas
From Vessels with Vapor
A
B
Data Collection
Shape of the vessel (Spherical / Cylindrical)
p_v [Pa] – Absolute Internal pressure of the Vessel
p_0 [Pa] – Ambient Pressure
V_1 [m^3] – Volume of the vessel filled by gas
γ [--] – Gas Specific Heat
R [m] – Distance from the center of the vessel to the target
c_c/c_0 [--] – Ratio of the Speed of Sound in the compressed gas to the speed of sound in air (*)
Calculate Compressed Energy of the Gas
$E_x = \frac{2V_1(p_v - p_0)}{(\gamma - 1)}$
2 represents an effective increase in Ex because a surface burst is assumed
Calculate Sachs-scaled distance
$R_s = R\left(\frac{p_0}{E_x}\right)^{\frac{1}{3}}$
C
Is R_s>2 ?
No
Yes
For non-ideal gases (FROM C), near field refinement for Rs < 2 is not valid
No
A more sophisticated method needs to be used
Calculate $\left(\frac{c_c}{c_0}\right)^2$
Calculate $\left(\frac{p_v}{p_0}\right)^2$
Determine non-dimensional starting peak pressure ΔP_{s0} from Fig. C-7
Calculate the starting distance
$r_0 = \left(\frac{3V_v}{2\pi}\right)^{\frac{1}{3}}$
Radius of the hemisphere of the same volume Vv as the vessel
Calculate the scaled starting distance
$R_{s0} = r_0\left(\frac{p_0}{E_x}\right)^{\frac{1}{3}}$
To take into account the fact that the vessel's placement is slightly above ground DPs is multiplied by 1.1
Use ΔP_{s0} and R_{s0} in Fig. C-8 to select the proper curve
Read the scaled side-on pressure; from Fig. C-5 and
$\Delta P_s = \left(\frac{p}{p_0}\right) - 1$
The side-on impulse I_s from Fig. C-6
Adjust p_s and I_s for geometry Effects according to Table C-3
Calculate absolute side-on peak pressure p_0
$\Delta P_s = P \cdot p_0$
Calculate unscaled side-on impulse
$I = \frac{(I_{sp0} p_0^{\frac{2}{3}} E_x^{\frac{1}{3}})}{c_0}$
Check P for reasonableness
Sometimes, the calculated value of P can exceed pv, the absolute pressure in the vessel. In that case, pv should be taken as the upper limit for P.

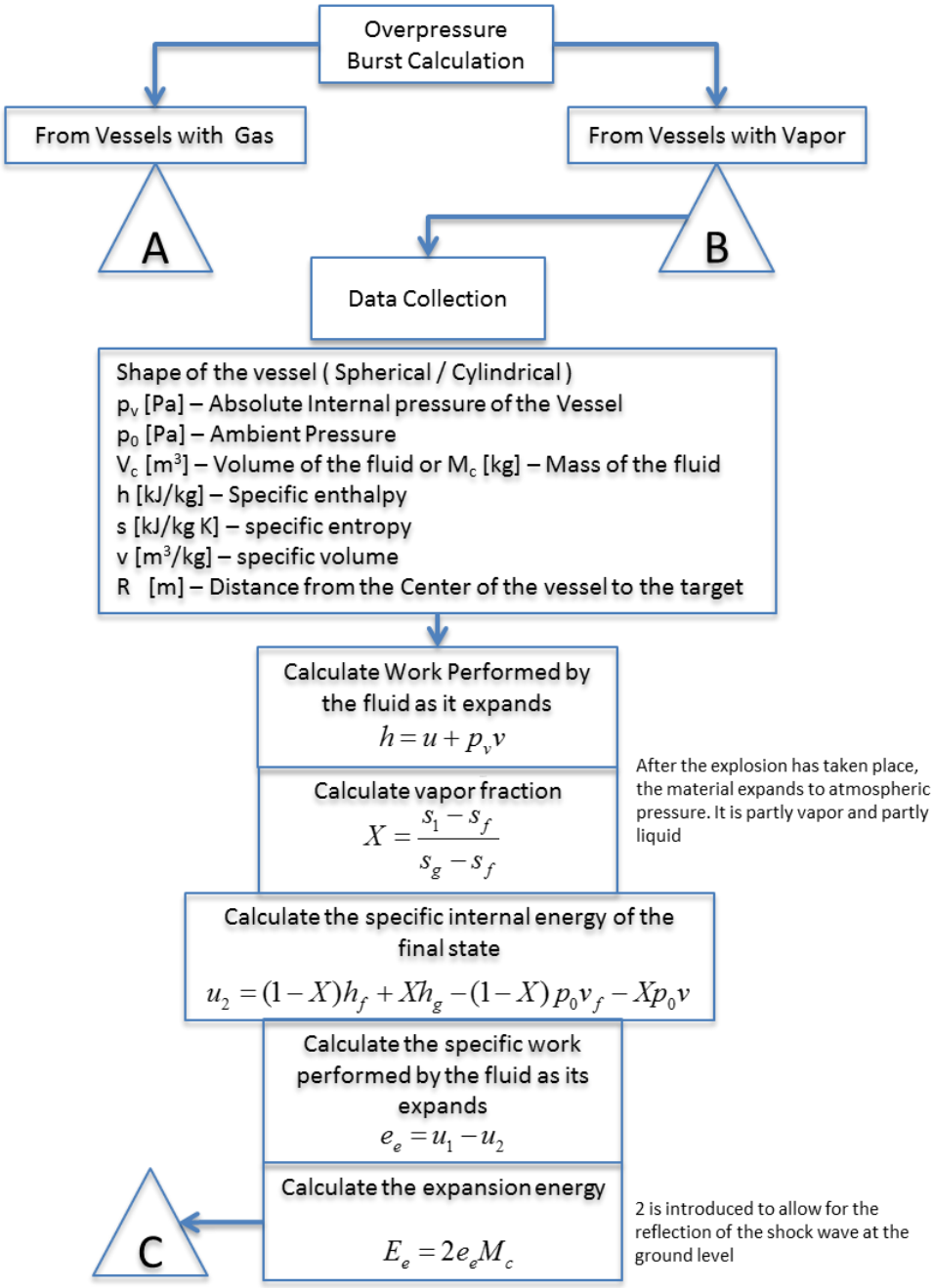


Figure C-4. Methodology for Blast Properties Calculation from Bursting Gases (~ideal gas) and vapors (non-ideal gases).

The following Figure C-5, Figure C-6, Figure C-7, Figure C-8,and Table C-3 are referenced above and are representative of the described methodology.

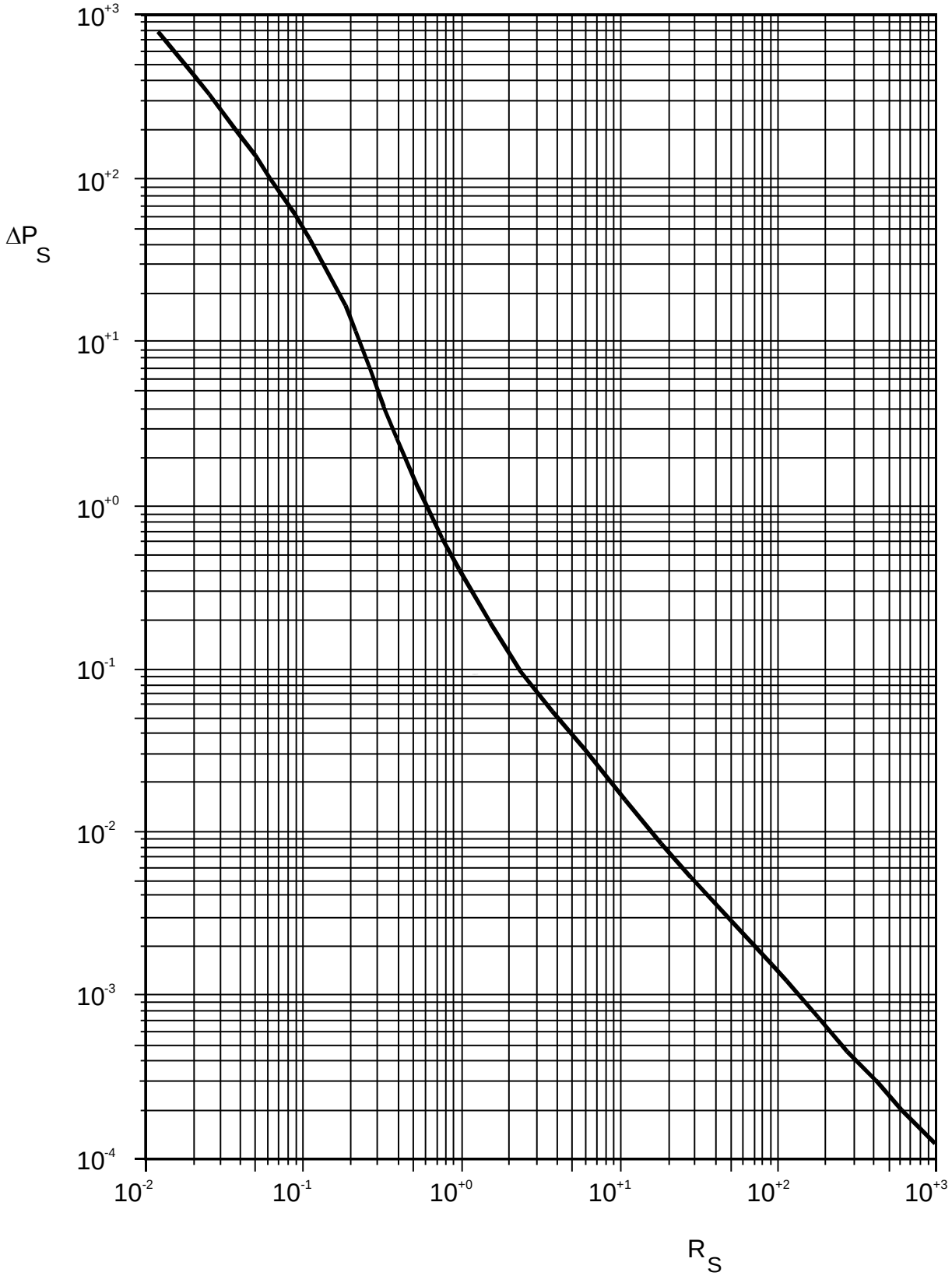


Figure C-5. ΔPs versus Rs for Penotlite.

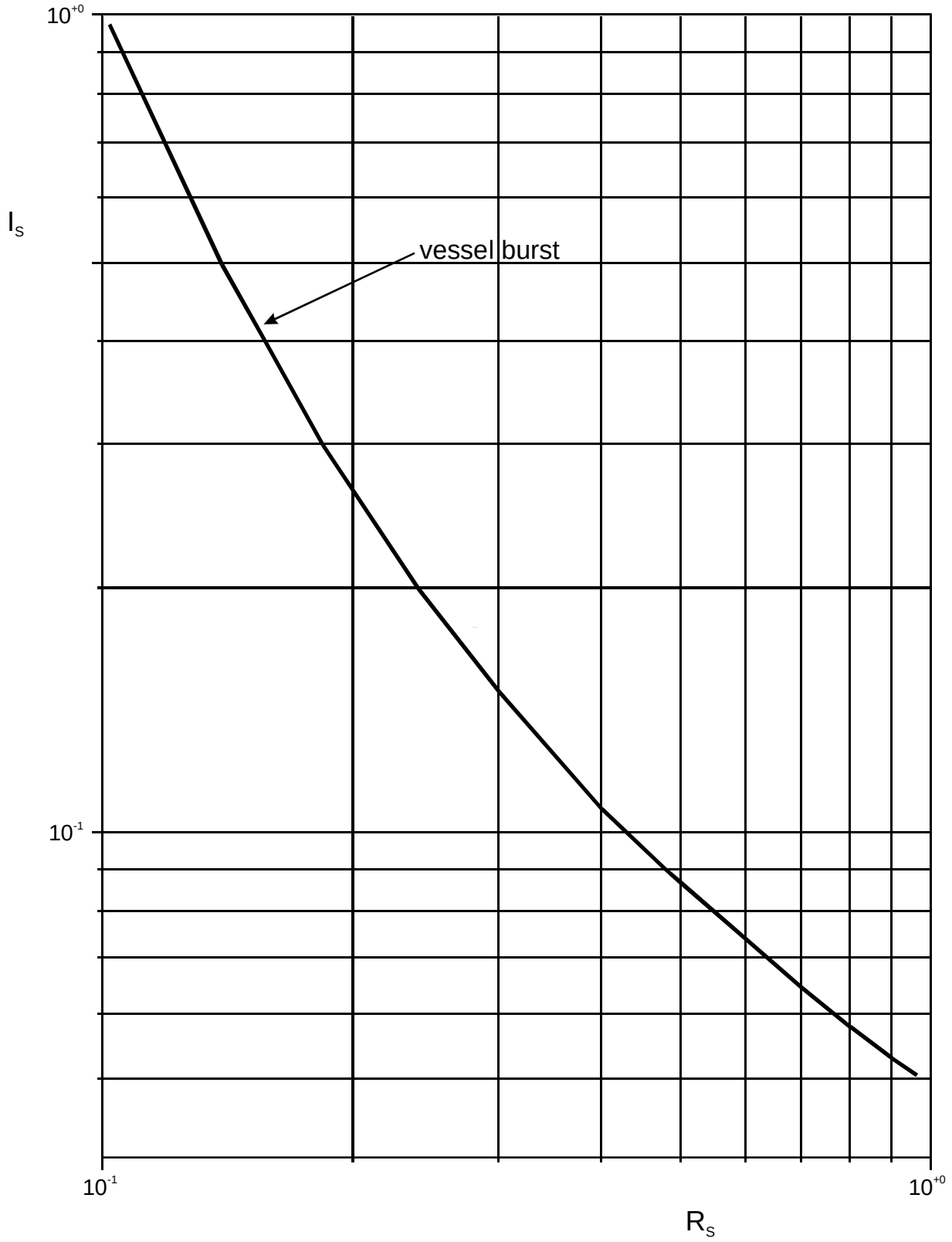


Figure C-6. Is versus Rs for Gas Vessel Bursts.

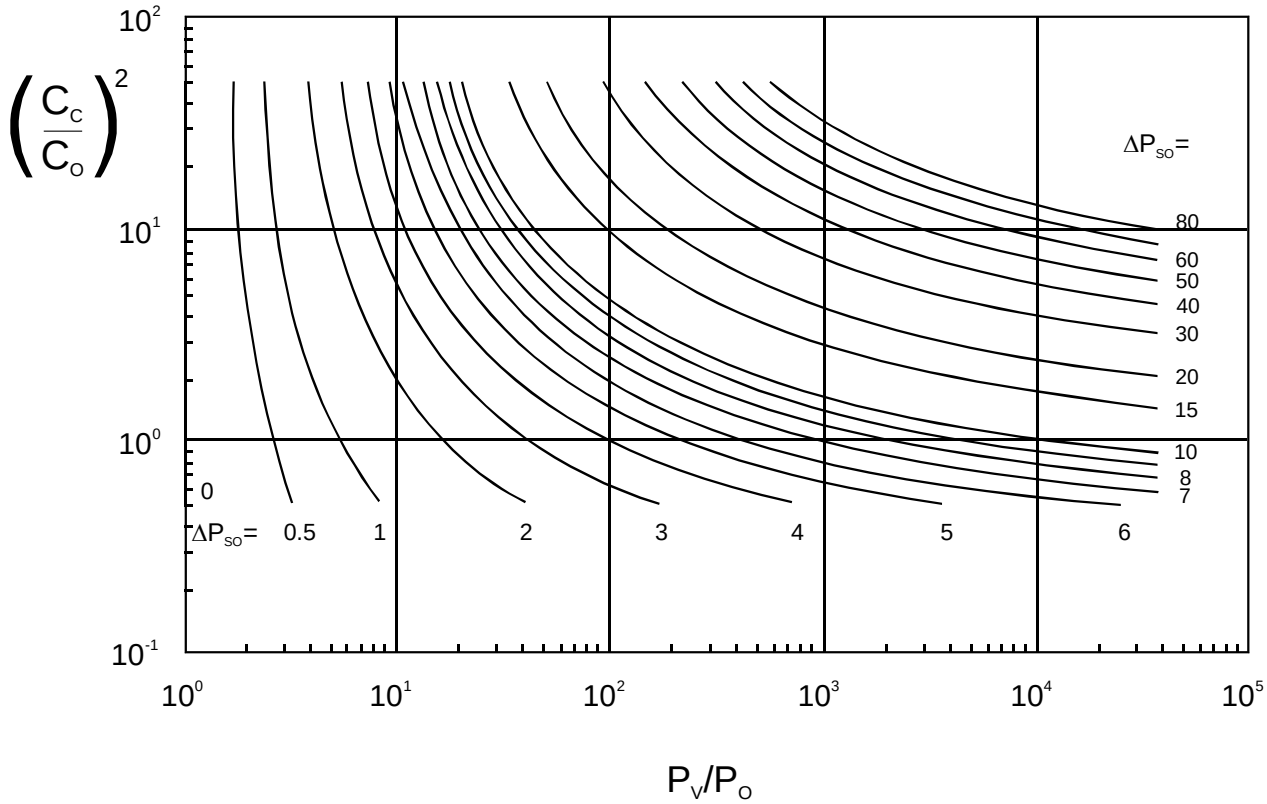


Figure C-7. Square of Speed of Sound Ratios versus Pressure for Constant ΔP_{s0} for γ = 1.4.

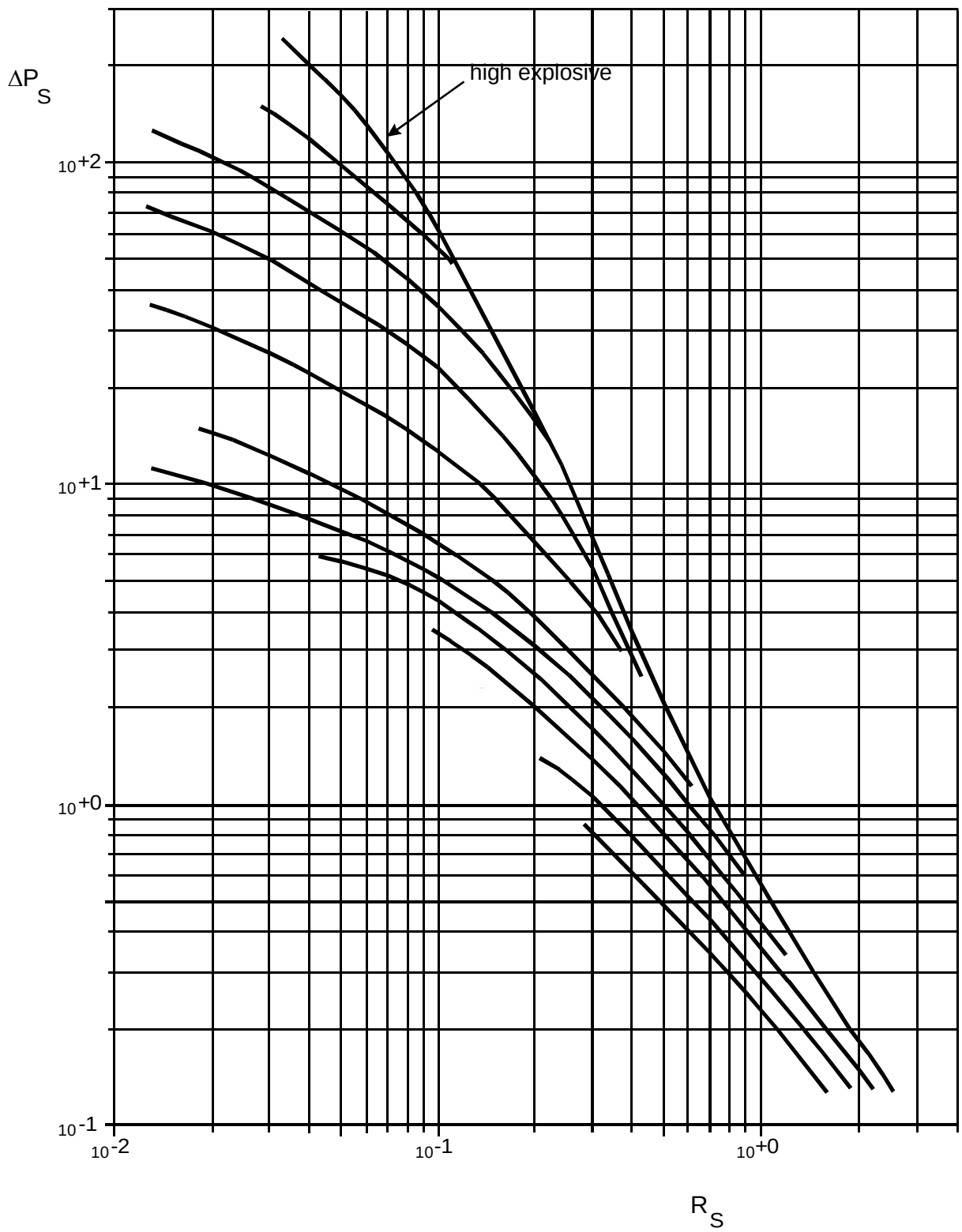


Figure C-8. Non-dimensional Overpressure versus Non-dimensional Distance for Overpressure.

Table C-3. Adjustment Factors for ΔPs and Is for Cylindrical and Spherical Vessels based on Rs.

Vessel Type	Rs	Multiply for:	
		ΔPs	Is
Cylindrical	< 0.3	4	2
	0.3 to 1.6	1.6	1.1
	1.6 to 3.5	1.6	1
	> 3.5	1.4	1
Spherical	< 1	2	1.6
	> 1	1.1	1

C.3.3 THERMAL RADIATION EFFECT FROM BLEVE

Fireball Diameter and Duration

In order to simplify calculations of BLEVE effects, it is often assumed that the fireball touches the ground, the fireball is spherical and its center is at height $D_c/2$. This should give a somewhat conservative estimate of radiant heat flux. Note that in practice the fireball rises as a function of time and that greater accuracy requires the use of numerical models.

The fireball diameter and its duration can be calculated by the following equations (Roberts, 1982; Pape, et. al., 1988):

$$D_c = 5.8 m_f \qquad \textbf{Equation C-13}$$

$$t_c = 0.45 m_f^{1/3} \text{ for } m_f < 30{,}000 \text{ kg} \qquad \textbf{Equation C-14}$$

$$t_c = 2.6 m_f^{1/6} \text{ for } m_f > 30{,}000 \text{ kg} \qquad \textbf{Equation C-15}$$

Where:

D_c [m] – final fireball diameter

m_f [kg] – mass of fuel in fireball

t_c [s] – duration of fireball

Damage Distance Calculation

From the equations to determine q (heat flux) and F (view factor) the hazard distance, L (i.e., the maximum distance at which that level of damage will occur) can be calculated as:

$$L = \left(\frac{D_c}{2}\right)\sqrt{\left(\frac{E \cdot \cos\Theta \cdot \tau_a}{q}\right)} \qquad \textbf{Equation C-16}$$

For hydrocarbon BLEVEs, the following empirical, simplified formula for the hazard range that could inflict severe burns to people was developed (Lihou and Maund, 1982):

$$L \sim 3.6 m_f^{0.4}$$ **Equation C-17**

Heat Flux

Finally, the rate at which a receptor receives thermal radiation or the heat flux that causes a specific level of damage in time ta is given by:

$$q = E_s \cdot F \cdot \tau_a$$ **Equation C-18**

Where:

q [kW/m^2] – rate at which thermal radiation is received by the receptor/incident radiant heat flux

E_s [kW/m^2] – surface emissive power. A value of 350 kW/m^2 for E_s is consistent with experiments on BLEVEs for most hydrocarbons involving a vapor mass of 1,000 kg or more.

$F = D_c^2 \cos\Theta / 4L^2$ [dimensionless] – View factor. For a point on a plane surface at a distance L from the center of a spherical fireball (with no obstructions between)

Θ is the angle between the normal to the surface and the line connecting the point to the center of the fireball.

τ_a [dimensionless] – atmospheric transmissivity

RH is the relative humidity

$$\tau_a = \log\left[14.1 \cdot RH^{-0.108}\left(L - \frac{D_c}{2}\right)^{-0.13}\right]$$ **Equation C-19**

Fuel Contribution to Fireball

A simple rule of thumb is that the amount of gas in a BLEVE can be taken to be three times the flash fraction, up to a limit of 100 percent (Hasegawa and Sato, 1977).

C.3.4 ANALYSIS OF FRAGMENTATION FROM EXPLOSIONS

When a high explosive detonates, a large number of small fragments reach high velocity. A BLEVE produces a relatively small number of fragments, some of which can contain a significant fraction of the mass of the vessel. These large fragments can travel long distances, sometimes nearly 1 km. In some cases (e.g., the rupture of a compressed air system consisting of pipes and spheres with a total mass of 145 MT), some fragments had a mass in excess of 10 MT.

There are a number of uncertainties associated with any attempt to characterize the properties of fragments after a vessel rupture:

- The fraction of the explosion energy which contributes to fragment generation is unclear. Its effect on initial fragment velocity, together with such factors as conditions in the vessel and the properties of the vessel's materials of construction are not known.
- Methods do not exist to predict the number of fragments produced. The effects of variables such as material, wall thickness and initial pressure are not known.
- Even if the effects of all these variables were known, the outcome of any given incident would be unpredictable. It would only be possible to present a prediction of the probabilities of certain outcomes.

Ideally, the analyst would like to know the mass distribution of fragments, their shapes, initial velocity of each fragment and its angle of elevation. Once this information is known, it is in principle possible to calculate the trajectory and, for any site-specific situation, to determine which structures might be struck by the fragment. It would then further be possible, if desired, to perform structural analyses.

Analytical Analyses

A theoretical method for calculating range distance of fragments is described in CCPS, 1994. The analyst should keep in mind that the following assumption took precedent in the method development:

- Research on fragment parameters has been limited to pressurized vessels filled with ideal gases.
- Models for calculating the initial velocities and ranges of fragments are incomplete because they give no way of calculating the number of fragments and only provide one value of velocity for all fragments.
- A number of assumptions have to be made to calculate range (e.g., initial elevation of the fragment trajectory) without which unrealistically long ranges would result.

This analysis consists of the following steps, which are described in Figure C-9 for fragment calculations.

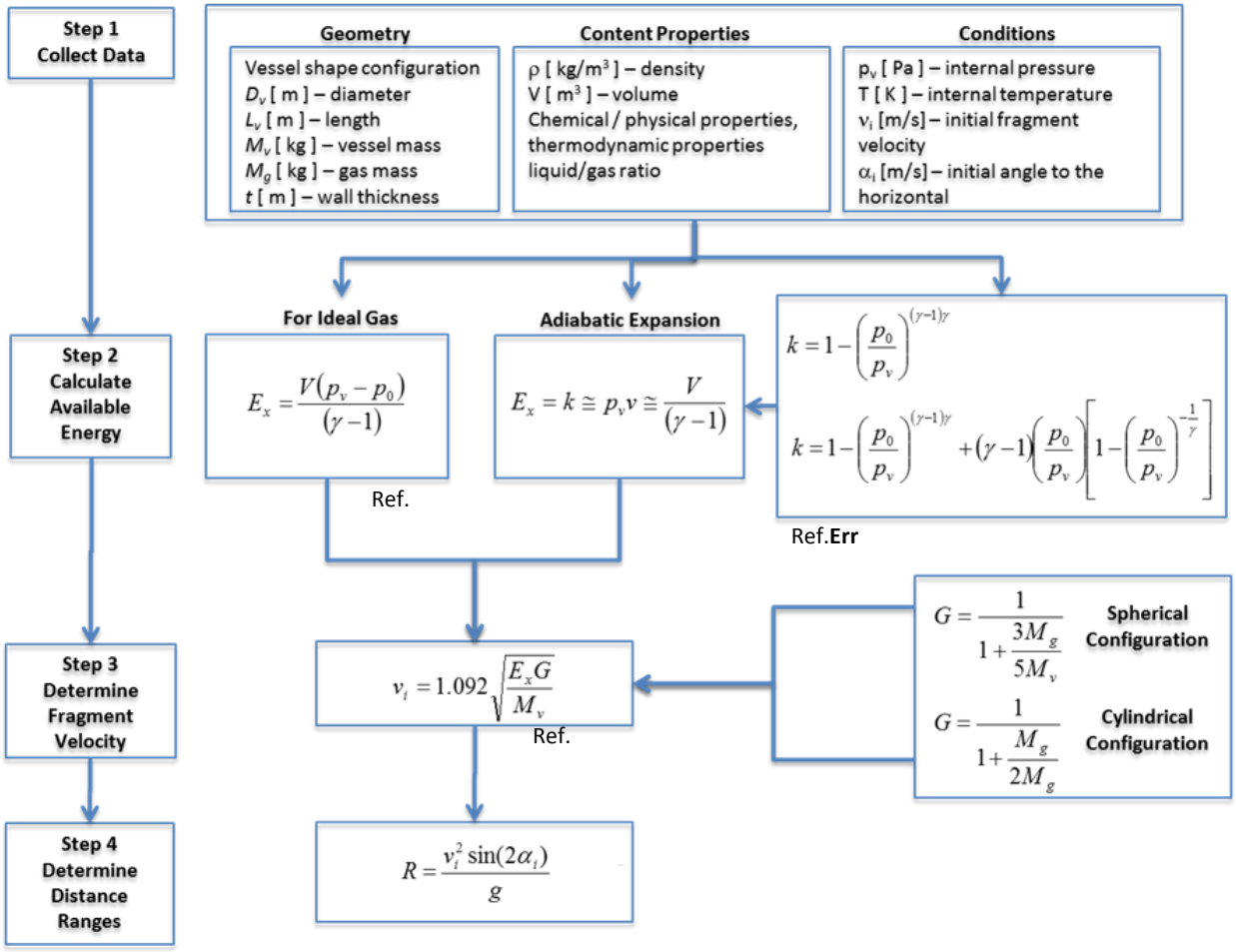


Figure C-9. Analytical Method for Fragment Calculations.

Statistical Analysis

In practice, there is only statistical information on which to base predictions of the fate of any fragments following a BLEVE or pressure vessel explosion.

An analysis in *Workbook for Predicting Pressure Wave and Fragment Effects of Exploding Propellant Tanks and Gas Storage Vessels*, (Baker et. al., 1977), considered 20 accidental explosions. Its data was organized into six groups, which are summarized in Table C-4.

Table C-4. Groups of Like Events—Fragments from Explosions (Baker, et. al., 1978).

Group Number	Number of Events	Explosion Material	Source Energy Range (J)	Vessel Shape	Vessel Mass (kg)	Number of Fragments
1	4	Propane, anhydrous ammonia	1.5E+5 to 6E+5	Railroad tank car	25,000 to 83,900	14
2	9	LPG	3,800 to 4,000	Railroad tank car	25,500	28
3	1	Air	5E+11	Cylinder, pipe and spheres	146,000	35
4	2	LPG, propylene	550	Semi-trailer (cylinder)	6,300 to 7,800	31
5	3	Argon	2.4E+9 to 1.1E+10	Sphere	48 to 187	14
6	1	Propane	25	Cylinder	510	11

Statistical analyses were performed on each group to yield estimates of fragment range and mass distributions. Lognormal distributions of fragment range and mass are shown in Figure C-10 and Figure C-11 respectively.

Using this data the analyst can obtain helpful information; for example:

- For a specific vessel, determine which of the groups 1 through 6 it most closely resembles.
- Choose a specific percentile (e.g., 50 percent for the median case, 95 percent for a conservative case) and read off the corresponding range from
- Within this range, consider whether there are any structures that are particularly vulnerable to missiles, or groups of people who may be within range.

Consider whether any additional design or procedural measures to reduce the likelihood of the initial explosion or to protect the potential target are necessary. This is necessarily a qualitative analysis.

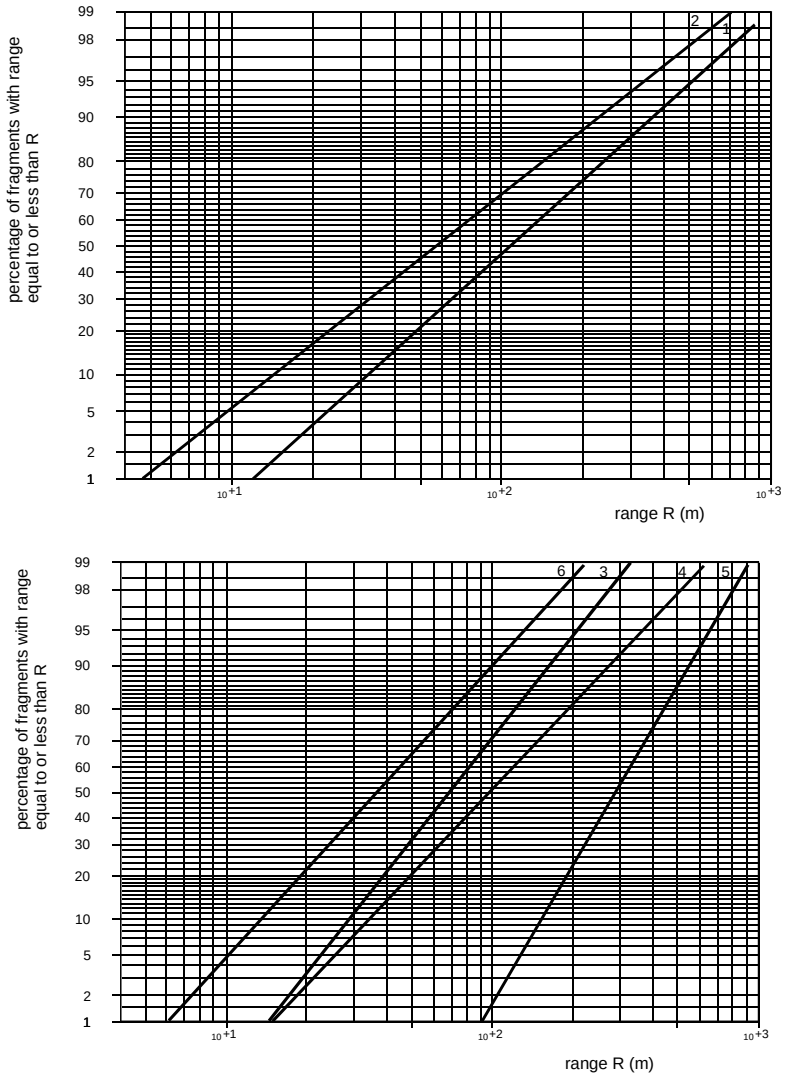


Figure C-10. Fragment Range Distributions (Baker, et. al., 1978).

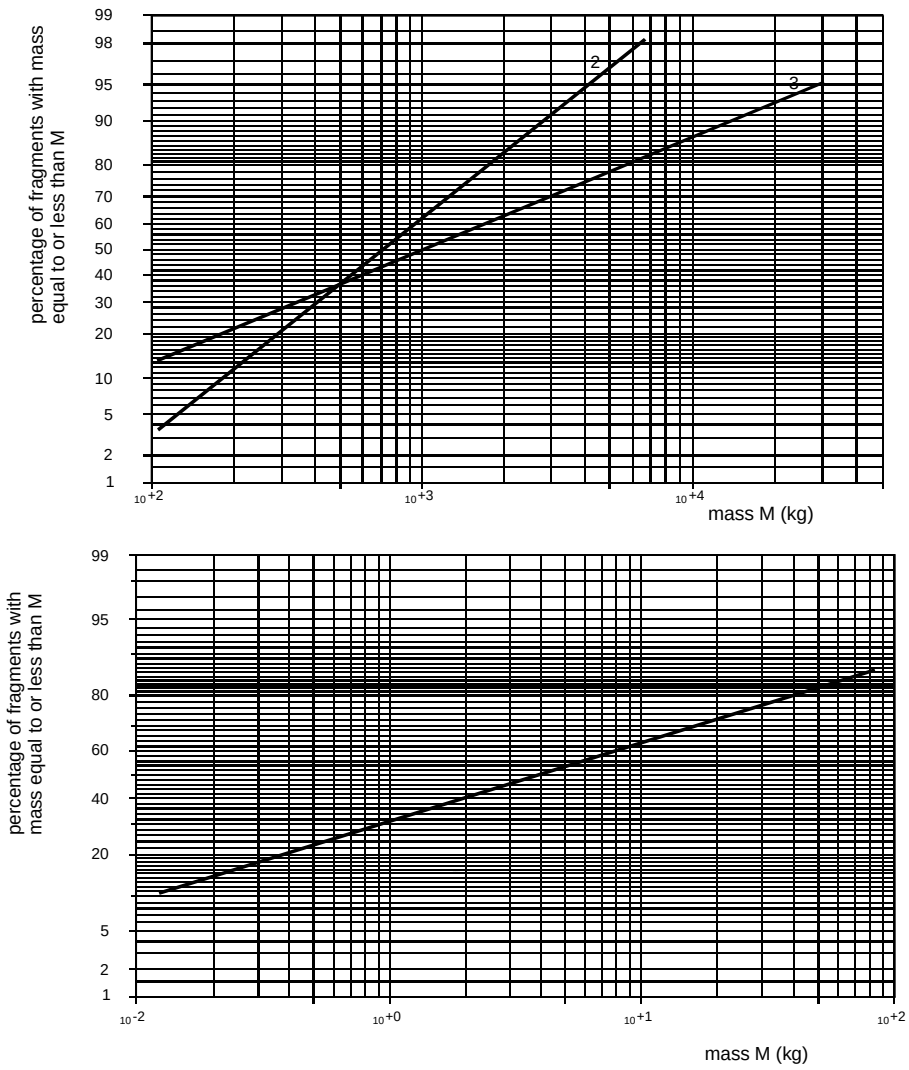


Figure C-11. Fragment Mass Distributions (Baker, et. al., 1978).

C.4 CONSEQUENCES OF EXPLOSIONS

C.4.1 DAMAGE CAUSED BY BLAST OVERPRESSURES

Table C-5 is suitable for use with simple models of explosions, such as TNT equivalency, or the Multi-Energy model where the sources of strong blast are modeled by TNT equivalency. This is satisfactory, as long as potential damage in the far field is the major concern. However, if the objective is to design blast-resistant structures, than both the blast wave's shape and positive-phase duration are important. These data should then be developed with a Computerized Fluid Dynamics (CFD) model and the structural response should be studied using a three-dimensional finite-element code such as DYNA3D (Whirley and Hallquist, 1991), which can treat a wide range of solid and structural mechanics problems.

Table C-5. Damage Produced by Air Blast.

Side-on Overpressure		Description of Damage
[psig]	[KPa]	
0.02	0.15	Annoying noise (137 dB if of low frequency, 10–15 Hz)
0.03	0.2	Occasional breaking of large glass windows already under strain
0.04	0.3	Loud noise (143 dB), sonic boom glass failure
0.1	0.7	Breakage of small glass windows under strain
0.15	1	Typical threshold for glass breakage
0.3	3	Safe distance (0.95 probability of no serious damage less than this value); projectile limit; some damage to house ceiling; 10 percent window glass breakage
0.4	3	Limited structural damage
0.5–1.0	3.5–7	Large and small windows usually shattered; occasional damage to window frames
0.7	5	Minor damage to house structure
1.0	8	Partial demolition of houses, made uninhabitable
1–2	7–15	Corrugated asbestos shattered; corrugated steel or aluminum panes fastening fail, followed by buckling; wood panel (standard housing) fastening fail, panel blown in
1.3	10	Steel frame of clad building slightly distorted
2	15	Partial collapse of walls and roofs of houses
2–3	15–20	Concrete or cinder block walls, not reinforced, shatter
2.5	18	Lower limit of serious structural damage, 50 percent destruction of brickwork of houses
3	20	Heavy machines (300 lb/1400 kg) in industrial buildings suffer little damage; steel frame building distorted and being pulled away from foundations
3–4	20–28	Frameless, self-framing steel panel buildings demolished; rupture of oil storage tanks
4	30	Cladding of light industrial buildings ruptured
5	35	Wooden utility poles snapped; tall hydraulic press (40,000 lb) in building slightly damaged
5–7	35–50	Nearly complete destruction of houses
7	50	Loaded tank cars overturned
7–8	50–55	Unreinforced brick panels, 8–12 in. (200–300 mm) thick, fail by shearing or flexure
9	60	Loaded train boxcars completely demolished
10	70	Probable total destruction of buildings; heavy machine tools (700 lb/3,200 kg) moved and badly damaged
300	2,070	Limit of crater lip

C.4.2 DAMAGE CAUSED BY EXPLOSIONS AND GLOVEBOXES

Glovebox explosion experiments were conducted that may have specific relevance to DOE accident analysis (Tuck, et. al., 1975). Raw data is presented in Table C-6.

Table C-6. Glovebox Explosion Experiments

TNT Equivalent	Explosion Inside Glovebox	Explosion Outside Glovebox
10–30 g	Rupture to bagout operations.	No damage.
30–60 g	Rupture to bagout and gloves to a distance of 7'. Top window and gasket windows blown out.	Minimum damage. Only bagout operations will be affected (5 to 11 ft).
60–90 g	All gloves ruptured, some structural damage to glovebox, some welds cracked.	About 25 percentof the gloves will be damaged (6 to 13 ft).
90–150 g	All bolted windows blown out, glovebox filters destroyed, glovebox severely damaged.	All gloves will be ruptured. Some damage to glovebox from heat (7 to 15 ft).
150–250 g	Near total damage to glovebox, some damage to supports, possible tears along welds near center of the blast.	Glovebox windows will be blown (8 to 18 ft).
250–450 g	Total damage to glovebox. Some internal equipment expelled.	Some damage to supports (10 to 22 ft).
450–1000 g	Total damage.	Box heavily damaged, some damage to adjacent areas (i.e., walls 13 to 27ft).
> 1000 g	Total damage.	Partial or total demolition of area (14 to 30 ft).

C.4.3 DAMAGE CAUSED BY THERMAL RADIATION

The consequences of thermal radiation may be simply assessed from Table C-7, which provides an estimate of the exposure time required to meet the pain threshold (API, 1982). The analyst can also find an excellent reference to tabulated values of various damages caused by thermal radiation in "Loss Prevention in the Process Industries – Hazard Identification, Assessment and Control," (Mannan, 2012).

Table C-7. Exposure Time t_c to Reach the Pain Threshold.

Radiation Intensity		t_c
[Btu/hr/ft^2]	[kW/m^2]	[s]
500	1.74	60
740	2.33	40
920	2.90	30
1,500	4.73	16
2,200	6.94	9
3,000	9.46	6
3,700	11.67	4
6,300	19.87	2

From the following Table C-8 can be observed that process equipment and buildings suffer severe damage for incident heat fluxes of 37.5 kW/m^2 and 12.5 kW/m^2 respectively. As a rule of thumb, flammable materials in buildings and process installations would be damaged after having been exposed to the above-quoted heat fluxes for longer than 1,000 s (Lihou and Maund, 1982).

Table C-8. Effects of Thermal Radiation (CCPS, 1989).

Radiation Intensity [kW/m^2]	Observed Effect
37.5	Sufficient to cause damage to process equipment. Minimum energy required to ignite wood at indefinitely long exposures
12.5	Minimum energy required for piloted ignition of wood, melting of plastic tubing, building damage
9.5	Pain threshold reached after 8 s. Second degree burns after 20 s.
4.0	Sufficient to cause pain to personnel if unable to reach cover within 20 s; however, blistering of the skin (second degree burns) is likely; 0 percent lethality
1.6	Will cause no discomfort for long exposure
1.0	Approximate solar radiation intensity on a clear, hot summer day

The criteria for thermal damage are shown in Table C-9 (CCPS, 1989). The referenced values were converted to thermal dose values. This is achieved by instituting an equal-area assumption, i.e. thermal radiation multiplied by time. The values to use for comparison of thermal damage to equipment are also shown in Table C-9.

Table C-1. Known Damage from Exposure to Thermal Dose.

Thermal Radiation (kW/m2)	Time of Exposure (sec)	Thermal Dose (kJ/m2)	Effects of Exposure
100	1800	180,000	Steel structure collapse
42	20	840	Spontaneous ignition of timber
35	600	21,000	Damage to process equipment, including steel vessels
25	600	15,000	Minimum energy to ignite wood
20	40	800	Ignition of fuel oil
18	600	10,800	Plastic cable insulation degrades
10	120	1,200	Ignition of fuel oil
References: (1) Kent, 2007, (2) LaChance, 2009, (3) Barry, 2003			

Thermal dose values pertinent to worker safety are shown in Table C-10 and in Figure C-12 (Hymes, 1983).

Table C-10. Worker Exposure to Thermal Dose.

Thermal Dose (kJ/m2)	Effects of Exposure
500	Third-Degree Burns (50 % Fatality)
250	Third-Degree Burns (1 % Fatality)
150	Second-Degree Burns
100	First-Degree Burns
40	Threshold of Pain

Source: Prugh, 1994

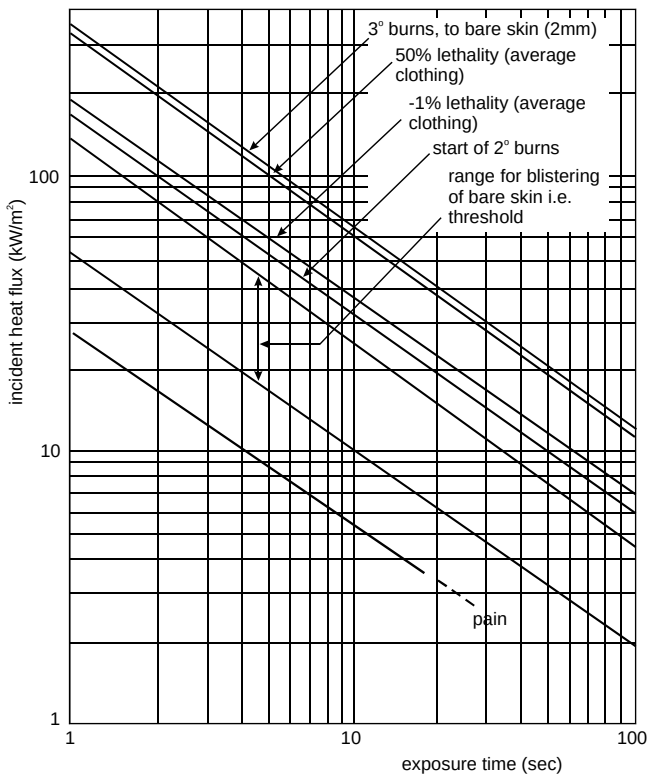


Figure C-12. Injury and Fatality Levels for Thermal Radiation (Hymes, 1983).

C.5 EXPLOSION CALCULATION EXAMPLES

There are many textbooks that give a basic introduction to explosions and their consequences.

It is strongly recommended that the analyst obtain copies of the Center for Chemical Process Safety's *Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires, and BLEVEs* (CCPS, 1994), or its successor guidance, *Guidelines for Vapor Cloud Explosion, Pressure Vessel Burst, BLEVE and Flash Fire Hazards*, 2nd Edition (CCPS, 2010), since they are clearly written and provide excellent guides to practical ways of calculating the effects of vapor cloud explosions, flash fires, and BLEVES.

The analyst shall be aware that the set of equations used in the Calculation Examples could be slightly different from those previously presented in the text, since the topic of explosions has been vastly studied and multiple sources and authors could be referenced. This, however, does not challenge the correctness of any of the equations since many of them were empirically obtained.

C.5.1 CALCULATION EXAMPLE OF A PRESSURE VESSEL RUPTURE

Background

A BHG system provides helium gas to end users throughout the Hotcells and Analytical Laboratories. High pressure gas cylinders store the helium gas in two separate banks. An automatic changeover regulator can switch from one bank to another and provide helium to the main distribution header. Pressure in the main distribution header is regulated by pressure control valves and pressure safety valves. System boundaries are typically located at the manual isolation valves on the various supply sub-headers and branches that connect the system to individual instruments and equipment.

The pressure vessel burst (PVB) effects considered are peak blast overpressures and impulses at various distances from the vessel, the initial velocity of vessel fragments, and fragment distances for a spectrum of launch angles. Only the effects of overpressure (side-on pressure and side-on impulse) and fragments born from a pressure vessel burst (velocity and range) are evaluated. No combustion effects (e.g. vapor explosion, fireball, etc.) are evaluated in this analysis due to the inert nature of helium.

Assumptions

Technically Justified Assumptions			
No.	**Assumption**	**Basis**	**Assumption Protection**
1.	The volume of He gas is taken as the entire volume of the cylinder	This maximizes the explosive forces in the pressure vessel burst.	This is a conservative assumption that does not require protection.
2.	The pressure that the cylinder fails at is 25 % higher than the maximum allowed working pressure (MAWP) of the vessel.	The vessel's burst pressure will typically be in the range of 3.5 to 4 times MAWP. However, temperature affects the strength of a vessel (higher temperatures make the metal yield more easily). The effect of high temperature on equipment strength can be very deleterious. For this reason, a pressure 25 % higher than the MAWP is assumed to fail the vessel.	This is a conservative assumption that does not require protection.
3.	The area of the vessel surface is assumed to equal the area of a cylinder, i.e., $2\pi rh$ plus the area of two, flat circular ends, each with an area of πr^2.	This will give an area that is larger than what would be calculated using the hemispherical end caps on the vessel and accounting for the offset due to the legs that are approximately 2 foot from the ground (i.e., the cylindrical portion of the vessel is only approximately 15 feet in height). As area increases, F also increases, as does the velocity of the fragment. This causes the range to increase.	This is a conservative assumption that does not require protection.
4.	All the energy within the cylinder is available to drive the blast wave.	Energy must be spent to rupture the vessel, propel its fragments, and accelerate the gases. In some cases the vessel expands in a ductile manner before bursting, thus absorbing additional energy. Should a vessel contain liquids or solids, a fraction of the available energy will be spent in propulsion of the	This is a conservative assumption that does not require protection.

		contents.	
5.	Vessel is cylindrical and at ground level		
6.	Distance from center of vessel to receptor, R, is 1 m.		
7.	The maximum ambient pressure and minimum ambient temperature inputs yield the most conservative results.	Pressure and temperature are inversely related. The models used in this calculation yield the most conservative results using maximum ambient pressure and minimum ambient temperature vs. minimum ambient pressure and maximum ambient temperature.	This is a conservative assumption that does not require protection.

Design and Analysis Input

Design Inputs		
Item	**Parameter**	**Value**
BHG cylinder	Cylinder type	1A
	internal volume	244 ft^3
	Volume of gas in cylinder at 1ATM	1424 ft^3
	Number of cylinders	10
	Empty weight of Matheson Tri-Gas 200 cylinder	117 lbs
	Maximum allowable working pressure MAWP (Design Pressure/Temperature)	135 psig at 160 ºF
	Normal operating pressure/temperature	120 psig at ambient temperatures
	outer diameter	9 in.
	height	51 in.

Analysis Inputs		
Parameter	**Value**	**Justification for Selection of Value**
Ratio of specific heats (c_p/c_v) for He, γ	1.667 (5/3)	Standard value for monatomic gases
Ratio of specific heats (c_p/c_v) for Air, γ	1.4 (7/5)	Standard value for mixtures of diatomic gases in air.
Ideal gas constant for He, R	2076.7 J/(kg· K)	Standard value
Acceleration due to gravity, g	9.8 m/s^2	Standard value
Speed of sound in air	3.4E+2 m/s	Standard value
Maximum atmospheric pressure at the WTP site	14.85 psia (0.09893977 MPa)	Standard maximum value for WTP site. Maximum overpressure is calculated with maximum ambient pressure

Analysis Inputs		
Parameter	**Value**	**Justification for Selection of Value**
Minimum Atmospheric temperature at the WTP site	23 °F (268.15 °K)	Minimum value for WTP site. Maximum range is calculated with minimum temperature

Calculations

Blast Effects from a Pressure Vessel Burst

1. Calculate the vessel-gas energy

The energy of a compressed gas in the vessel is calculated using a formula for free air explosions: For ground bursts, the energy is doubled to account for the ground reflection *(CCPS, 2010)*:

$$E = 2 \cdot \frac{(p_1 - p_0) V_1}{\gamma_1 - 1} = \frac{2(1.262 - 1.024E-01\,MPa)(3.823m^3)}{(1.66 - 1)} = 1.348E+01\,MJ$$

Equation C-20
(Equation 7.16, *CCPS, 2010*)

where

E is the energy of a compressed gas (MJ)
p_1 is the burst pressure of the vessel (MPa)
p_0 is the ambient pressure (MPa)
V_1 is the volume of the vessel (m^3)
γ_1 is the ratio of specific heats c_p/c_v (dimensionless)

2. Select the blast curve

Calculate the vessel burst pressure ratio (BPR), using:

$$BPR = \frac{p_1}{p_0} = \frac{(1.262\ MPa)}{1.024E-01\,MPa} = 12.36$$

Equation C-21
(Equation 7.5, *CCPS, 2010*)

Then locate the overpressure and impulse curves that correspond to the vessel burst pressure ratio in Figure C-13 and Figure C-14, respectively (taken from CCPS, 2010, Figures 7.6 and 7.7).

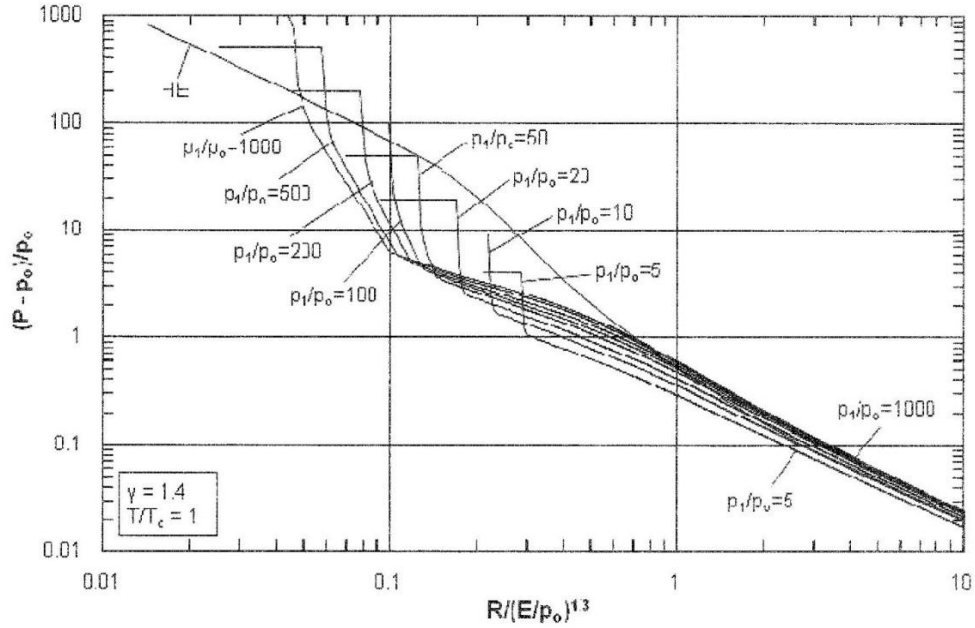


Figure 7.6. Positive overpressure curves for various vessel pressures. (Tang, et al. 1996)

Figure C-13. Negative Pressure Curves for Various Vessel Pressures. (taken from CCPS, 1010, Figure 7.6)

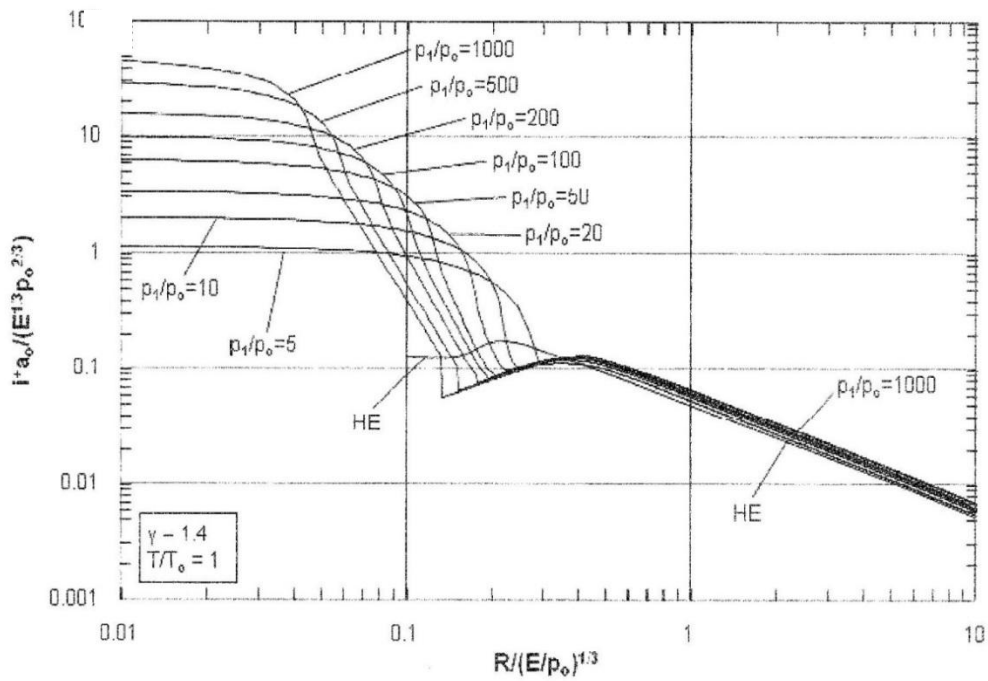


Figure 7.7. Negative pressure curves for various vessel pressures.

Figure C-14. Negative Pressure Curves for Various Vessel Pressures. (taken from CCPS, 1010, Figure 7.7)

The overpressure and impulse curves that most closely correspond to the vessel burst pressure ratio of 12.760 are the ones labeled p_1/p_0 = 10 in Figure 13 and Figure 14, respectively.

3. Calculate the scaled standoff distance $\overline{R}$ of the receptor

Calculate the scaled distance of the receptor $\overline{R}$ using:

$$\overline{R} = R\left[\frac{p_0^{1/3}}{E^{1/3}}\right] = (1.0\ \text{m})\left[\frac{(91.024\text{E-01 MPa})}{(1.348\text{E+01 MJ})}\right]^{1/3} = 1.966\text{E-01}$$

Equation C-22 (Equation 7.17 *CCPS, 2010*)

where R is the distance at which blast parameters are to be determined.

4. Determine scaled positive overpressure $\overline{P}_s$

To determine the scaled side-on overpressure, $\overline{P}_s$, use the curve from Figure 1 that corresponds to the vessel BPR p_1/p_0 and read $\overline{P}_s$ for the appropriate $\overline{R}$.

To determine the scaled positive overpressure, the curve in Figure 13 corresponding to a BPR of 10 will be used. Using the scaled distance of 0.1944 (~0.2), the scaled positive overpressure is found to be 10.

<u>Determine the scaled positive impulse $\overline{i}_+$</u>

To determine the scaled positive impulse, the curve in Figure 14 corresponding to a BPR of 10 will be used. Using the scaled distance of 0.1944 (~0.2), the scaled positive impulse is found to be 0.8.

<u>Adjust $\overline{P}_s$ and $\overline{i}_+$ for different initial conditions</u>

Figure 3 presents three charts depending on the length to diameter ratio of the vessel. The length or height of the cylinder is 1.295 m (51 in.) and the diameter is 0.2286 m (9 in.). This yields a ratio of 5.667. The curves presented for L/D of 5 should be used. However, due to range limitations of the L/D= 5 overpressure not presenting a value of 0.194 (~0.2) within the region of the graph, the L/D of 2 will be used for conservatism; erring on the side of a stouter physical geometry. Using the scaled distance of 0.194 (~0.2), the adjustment factor of the scaled positive overpressure is extrapolated from the graph to be 0.8. Similarly, the adjustment factor for the scaled positive impulse is determined to be 1.3 using the L/D = 5 graph.

5. Adjust $\overline{P}_s$ for different initial conditions such as vessel temperature and geometry

Elevated temperatures increase the positive overpressure near the vessel compared to the same vessel at ambient temperatures. However, the effect diminishes with distance from the vessel. If the target is far enough from the vessel, i.e., R > 1, adjustment for temperature is not necessary and the use of ambient temperature blast curves is adequate and conservative.

Early adjustments for geometry were based on high explosive data. In 2009, a group of adjustment factors specifically for PVB were developed. Figure C-15 shows adjustment curves for cylindrical free air PVB (taken from CCPS, 2010, Figure 7.10).

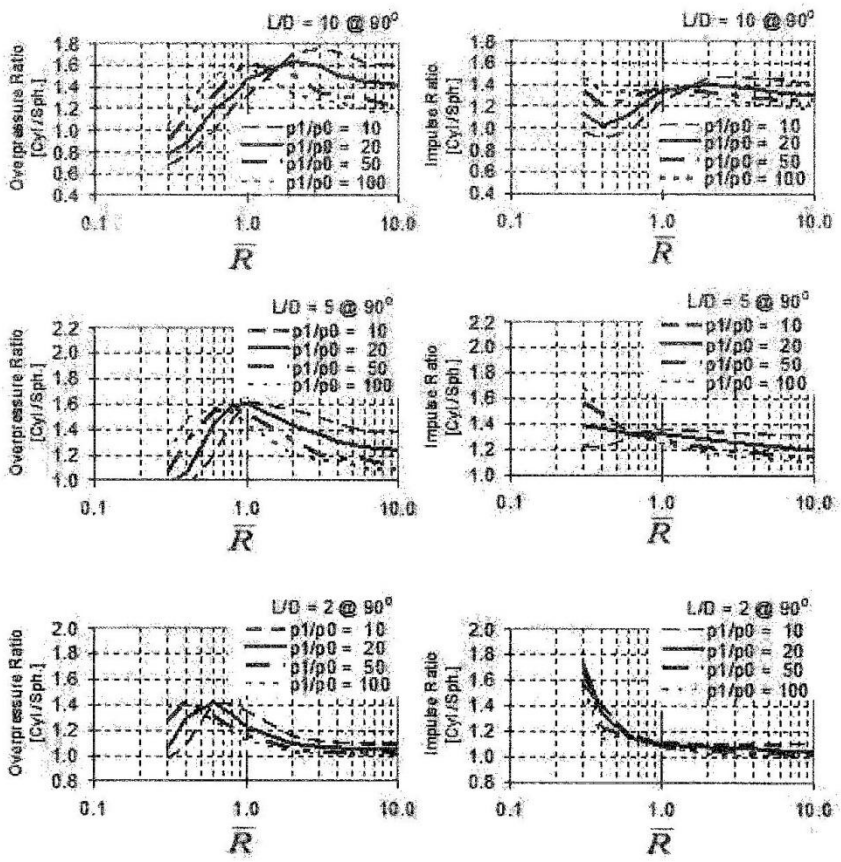


Figure 7.10. stment factors for cylindrical free air PVBs compared to a spherical free air burst. (Geng, 2009)

Figure C-15. Adjustment Factors for Cylindrical Free Air PVBs Compared to a Spherical Free Air Burst. (taken from CCPS, 1010, Figure 7.10)

The adjustment factor value is found from Figure 3 using the graphs for the appropriate L/D ratio. The scaled standoff $\overline{R}$ value is used with the curve corresponding to the appropriate p_1/p_0 to arrive at the adjustment factor for the overpressure, F_1, and for the impulse, F_2.

6. Calculate P_s and i_s

The side-on peak overpressure, P_s, is given by:

$$P_s = \overline{P_s} \cdot F_1 \cdot p_0 = (10)(0.8)(1.021E\text{-}01\ \text{MPa}) = 8.191E\text{-}01\ \text{MPa}$$

Equation C-23 (Equation 7.18 CCPS. 2010)

The side-on impulse i_s, is given by:

$$i_s = \frac{\bar{i} \cdot F_2 \cdot p_0^{2/3} \cdot E^{1/3}}{a_0} = \frac{(0.8)(1.3)(1.024E-01\ \text{MPa x } 1E+06\ \text{Pa/MPa})^{2/3}(13.48\ \text{MJ x } 1E+06\ \text{Pa/MPa})^{1/3}}{340\ \frac{m}{s}} = 1.593E+03\ \text{Pa} \cdot \text{s}$$

Equation C-24
(Equation 7.19 CCPS. 2010)

Fragments from a Pressure Vessel Burst

1. Calculate the speed of sound in the gas

The speed of sound in gas is:

$$a_1 = \sqrt{\frac{T \cdot \gamma \cdot R}{m}} = \sqrt{T \cdot \gamma \cdot R_{He}} = \sqrt{(268.15\ \text{K})(1.66)\left(2076.7\ \frac{J}{kg \cdot K}\right)} = 9.6146E+02\ \frac{m}{s}$$

Equation C-25
(Equation 7.28 CCPS. 2010)

where

T is the absolute temperature,
R is the ideal gas constant, and
m is the molecular weight of the gas. R_{He} is the ideal gas constant of helium; which specifically accounts for the molecular weight of helium.

2. Calculate the initial velocity of the fragment

In order to calculate the initial velocity, the surface area of the vessel needs to be calculated so that the mass per unit area can be calculated. Technically justified assumption 3 says the area of the vessel can be conservatively estimated using the area of a cylinder plus the area of two circles. Thus, the surface area of the vessel is:

$$A = 2\pi \cdot rh + 2\pi r^2 = 2\pi\left(rh + r^2\right) = (2\pi)\left[(0.1143m)(1.295m) + (0.1143m)^2\right] = 1.01\ m^2$$

The mass per unit area of the vessel, m, is then found by dividing the mass of the empty vessel by the surface area of the vessel calculated above.

$$m = \frac{5.307E+01\ kg}{1.01 m^2} = 52.42\ \frac{kg}{m^2}$$

The initial velocity of the fragments is based upon empirical relations. For the disintegration of both cylindrical and spherical vessels into multiple fragments:

$$v_i = 0.88\ a_1\ F^{0.55}$$

Equation C-26
(Equation 7.29 CCPS. 2010)

where F (a parameter corresponding to the number of fragments) is found using:

$$F = \frac{(p_1 - p_0)\ r}{m\ a_1^2}$$

Equation C-27
(Equation 7.32 CCPS. 2010)

where r is the radius of the vessel, and m is the mass per unit area.

Combining Equations C-26 and C-27 yields the initial velocity of the fragment:

$$v_i = 0.88\, a_1 \left[\frac{(p_1 - p_0)\, r}{m\, a_1^2} \right]^{0.55} = 0.88 \left(9.615E+02 \frac{m}{s} \right) \left[\frac{(1.266 - 1.024E-01\, MPa)\left(1 \times 10^6 \frac{Pa}{MPa}\right)(1.143E-01\, m)}{\left(52.42 \frac{kg}{m^2}\right)\left(9.615E+02 \frac{m}{s}\right)^2} \right]^{0.55} = 33.0 \frac{m}{s}$$

Equation C-28

3. Calculate the range of the fragment

The simplest relationship for calculating the fragment range neglects drag and lift forces. The horizontal range, R, depends upon the initial velocity, v_i, and the initial trajectory angle, α_i:

$$R_{5_deg} = \frac{v_i^{\,2} \sin(2\alpha_i)}{g} = \frac{\left(33.0 \frac{m}{s}\right)^2}{9.8 \frac{m}{s^2}} \cdot \sin\left(2\pi \frac{5^\circ}{180^\circ}\right) = 1.930E+01\ m$$

Equation C-29
(Equation 7.40 CCPS. 2010)

The trajectory angle has a great influence on the range. The maximum range is found for an angle of 45 degrees. This simplifies Equation 10 into:

$$R_{max} = \frac{v_i^{\,2}}{g} = \frac{\left(33.0 \frac{m}{s}\right)^2}{9.8 \frac{m}{s^2}} = 1.111E+02\ m$$

Equation C-30
(Equation 7.41 CCPS. 2010)

Maximum Fragment Ranges as a Function of Trajectory Angle

Range (5°)	1.930E+01 m
Range (10°)	3.801E+01 m
Range (15°)	5.557E+01 m
Range (20°)	7.144E+01 m
Range (25°)	8.514E+01 m
Range (30°)	9.626E+01 m
Range (35°)	1.044E+02 m
Range (40°)	1.095E+02 m
$Range_{max}$ (45°)	1.111E+02 m

Results and Conclusions

These calculated consequences are presented in the next table.

Consequences of Pressure Vessel Bursts

Vessel	Side-on Peak Overpressure P_s (MPa)	Side-on Impulse i_s (Pa·s)	Initial Velocity of Fragments v_i (m/s)	Maximum Range of Fragments R_{max} (m)
Single Helium Cylinder	8.2E-01	1.6E+03	33.0	1.11E+02

Uncertainty and Conservatisms

Graph readings from *Guidelines for Vapor Cloud Explosion, Pressure Vessel Burst, BLEVE, and Flash Fire Hazards* (CCPS, 2010) are only precise to within 1 significant digit due to the limitations of the graphs.

The minimum or maximum value for atmospheric inputs are used to calculate the most conservative overpressures and ranges even if the atmospheric conditions cannot necessarily occur in nature at the same time.

Consequence calculations are highly assumption driven and because of this are uncertain. This leads to conservative calculations. This subsection discusses the degree of conservatism believed to be present in the calculation. Also discussed are any uncertainties, however, detailed quantification of uncertainty is not required. This subsection will be addressed for this calculation.

Consequence Comparison

The following table shows several values for damage expected from overpressure.

Known Damage from Exposure to Overpressure		
Overpressure		**Expected Damage**
psig	**atm**	
1.0-2.0	0.068-0.136	Corrugated metal panels buckle and fail Wood panels on standard houses blown in
2.0-3.0	0.136-2.041	Concrete or cinder block walls, not reinforced, shattered
3.0	0.204	Steel building distorted and pulled away from foundation
4.0-7.0	0.272-0.476	Major damage on steel construction objects
5.0	0.340	Wooden utility poles snap
5.8-8.7	0.394-0.592	Heavy damage on reinforced concrete buildings
References: (1) K-H, 2001, (2) OGP, 2010, (3) Chang, 2010		

C.5.2 CALCULATION EXAMPLE OF A BLEVE EXPLOSION

Background

This calculation estimates the effects of overpressure and fragments born from an ammonia Boiling Liquid Expanding Vapor Explosion (BLEVE). In addition, since anhydrous ammonia is flammable, the thermal effects of a fireball is examined to understand the potential damage to nearby structures and the expected effects on personnel.

To determine the destructive potential of a BLEVE for safety or design purposes, the worst case circumstances are evaluated. It is often a misconception that the BLEVE produces the pressure that results in a catastrophic vessel failure. A BLEVE occurs independently of a vessel failure. That is, the explosion does not cause the vessel to fail, it is the failure of a vessel that leads to a sudden depressurization of superheated liquid. As such, the energy release calculated is two-fold, one of mechanical (expansion) and one of combustion (if there is a combustible or flammable fluid ignited).

Assumptions

Technically Justified Assumptions			
No.	**Assumption**	**Basis**	**Assumption Protection**
1	A Yield Factor (YF) of 0.1 is used to determine the initial velocity of the fragments.	It is appropriate to use a YF when determining the explosive change for material other than that which would produce a condensed phase explosion. This practice is conducted in the chemical industry and has been presented to the Energy Facility Contractors Group (EFCOG). CCPS references range from 0.01 to 0.2 for various gases and vapors under various conditions An unconfined vapor cloud explosion of ammonia should probably use a YF of 0.03; however, even with an atmospheric release, trees, buildings, terrain, etc., can create partial confinement conditions (Muhlbauer, 2004). The 0.1 is used for partially confined vapor cloud explosions of moderately reactive gases (CCPS, 1989).	A YF of 0.1 is used for partially confined vapor cloud explosions of moderately reactive gases (CCPS, 1989), which provides a reasonable amount of conservatism.
2	The burst pressure of the ammonia vessel is assumed to be 400 psig.	"Second Report of the Advisory Committee on Major Hazards"(HSE, 1979) recommends using a vessel failure pressure for storage vessel with properly sized relief valves of 1.21 times the relief valve set pressure. The set point for the pressure relief is shown to be 300 psig in design drawing xxx. Addressing a burst pressure of 400 psig exceeds the recommendation; therefore, it is conservative.	A burst pressure of 400 psig is reasonable amount of conservatism.

Technically Justified Assumptions			
No.	**Assumption**	**Basis**	**Assumption Protection**
3	The effects of thermal dose on construction materials can be approximated by assuming equal areas (under the curve) of referenced thermal radiation and exposure times.	A thermal dose is defined as the integral of the thermal flux over the exposure time. Experiments for the effects of thermal radiation generally include the application of a constant heat flux to a target for a period of time. The experimental results are presented as the amount of time for a particular effect to occur with the applied thermal radiation. For experimental data, the product of the thermal flux and the exposure time is quite effectively the thermal dose. The assumption means that the referenced damage can be effectively bounded by events of high heat flux over short time durations, as well as low heat flux over long time durations. Furthermore, the assumption means that the referenced damage can be defined with a thermal dose, i.e., the product of thermal radiation and the exposure time (see Table C-9). Per engineering judgment, such a statement is accurate for construction materials as long as no target experiences a phase change and targets are not thermally thin[49].	This is a conservative analytical assumption and does not require protection.

Design and Analysis Input

Confirmed Design Input	
Parameter	**Value**
Vessel Volume (each vessel)	6,000 gal
Pressure Relief Set Point	300 psig

Preliminary Design Input	
Parameter	**Value**
Vessel Empty Weight, New	26,041 lb (11,812 kg)

Analysis Inputs		
Parameter	**Value**	**Justification for Selecting Value**
Molecular Weight of Ammonia (NH_3)	17.03 g/gmole	Standard Value
Heat of Combustion for NH_3	-382.58 kJ/mol (gas)	Standard Value
Heat of Combustion for Propane	-2220.0 kJ/mol (gas)	Standard Value

[49] Thermally thin means there is no thermal gradient will exist inside of an object exposed to a heated environment, i.e., the Biot number is less than 0.1.

Analysis Inputs		
Parameter	**Value**	**Justification for Selecting Value**
Thermodynamic Properties for liquid Ammonia at 1 bar (T_{sat} = -33.60 °C)	s_L =5.1043 J/g-K h_L =-914.84 J/g u_L =-914.98 J/g v_L =1.46636 L/kg	Standard Value
Thermodynamic Properties for vapor Ammonia at 1 bar (T_{sat} = -33.60 °C)	s_g =10.8249 J/g-K h_g =455.52 J/g u_g =341.72 J/g v_g =1137.99 L/kg	Standard Value
Thermodynamic Properties for liquid Ammonia at 27 bar (T_{sat} = 61.33 °C)	s_L =6.6704 J/g-K h_L =-463.40 J/g u_L =-468.37 J/g v_L =1.84248 L/kg	Standard Value
Thermodynamic Properties for vapor Ammonia at 27 bar (T_{sat} = 61.33 °C)	s_g =9.6287 J/g-K h_g =526.09 J/g u_g =398.74 J/g v_g =47.17 L/kg	Standard Value
Thermodynamic Properties for liquid Ammonia at 28 bar (T_{sat} = 62.84 °C)	s_L =6.6934 J/g-K h_L =-455.48 J/g u_L =-460.67 J/g v_L =1.85205 L/kg	Standard Value
Thermodynamic Properties for vapor Ammonia at 28 bar (T_{sat} = 62.84 °C)	s_g =9.6130 J/g-K h_g =525.45 J/g u_g =398.39 J/g v_g =45.38 L/kg	Standard Value
Low Ambient Humidity	10%	This value is low within the range discussed in reference. It provides a realistically conservative value for thermal transmissivity.
Low Ambient Temperature	1 °C	This value is low within the range discussed in reference. It provides a realistically conservative value for saturated water vapor pressure used in determining the thermal transmissivity.
Standard Atmospheric Pressure	101,325 Pa	Standard Value
Water vapor pressure at Low Ambient Temperature	660 Pa	Standard Value for 1 °C
Density of Steel	8,050 kg/m^3	High end of range. The value is used to determine the physical dimensions of the steel fragments, which contributes to the ability to penetrate steel.
Ultimate Compressive Strength of Concrete	4000 psi (28 MPa)	Low end of range for structural concrete with multistrand tendons. This value provides a realistically conservative penetration in concrete.

Calculations

Mechanical Work Due to Expansion and Combustion of Superheated Fluid

Assuming an isentropic expansion, the total work done by the superheated liquid during the expansion process is given by the following:

$$W = -\Delta U$$ **Equation C-31**

Where:

W is the work done by the system on the surrounding (kJ)
ΔU is the change in the internal energy of the expanding fluid (kJ)

The specific internal energy (u) at a specific state may be obtained directly from thermodynamic tables. The thermodynamic states are defined with pressure and temperature. The change in the internal energy (ΔU) is then estimated from the following:

$$\Delta U = \left(m_{g,2}u_{g,2} + m_{L,2}u_{L,2}\right) - \left(m_{g,1}u_{g,1} + m_{L,1}u_{L,1}\right)$$ **Equation C-32**

Where:

$m_{L,i}$ is the liquid mass at state i (kg)
$m_{g,i}$ is the vapor mass at state i (kg)
uL,i is the liquid-specific internal energy at state i (kJ/kg)
ug,i is the vapor-specific internal energy at state i (kJ/kg)

Table C-11. Thermodynamic Values for Ammonia.

P (bar)	T (°C)	u_L (J/g)	u_g (J/g)	s_L (J/g-K)	s_g (J/g-K)	v_L (L/kg)	v_g (L/kg)
27	61.33	641.894	398.74	2.46792	9.6287	1.84248	47.17
28	62.84	649.594	398.39	2.49092	9.613	1.85205	45.38

Linear interpolation was used to determine the thermodynamic values at the assumed failure pressure of 400 psig (27.5862 bar). This is the initial state discussed in Table C-11.

$$u_L\left(\tfrac{J}{g}\right) = \frac{(649.594 - 641.894)\left(\tfrac{J}{g}\right)}{(28-27)\,\text{bar}} \cdot (27.5862 - 27)\,\text{bar} + 641.894\left(\tfrac{J}{g}\right)$$ **Equation C-33**

$$u_g\left(\tfrac{J}{g}\right) = \frac{(398.39 - 398.74)\left(\tfrac{J}{g}\right)}{(28-27)\,\text{bar}} \cdot (27.5862 - 27)\,\text{bar} + 398.74\left(\tfrac{J}{g}\right)$$ **Equation C-34**

$$s_L\left(\tfrac{J}{g\cdot K}\right) = \frac{(2.49092 - 2.46792)\left(\tfrac{J}{g\cdot K}\right)}{(28-27)\,\text{bar}} \cdot (27.5862 - 27)\,\text{bar} + 2.46792\left(\tfrac{J}{g\cdot K}\right)$$ **Equation C-35**

$$s_g\left(\frac{J}{g\cdot K}\right)=\frac{(9.6130-9.6287)\left(\frac{J}{g\cdot K}\right)}{(28-27)\,\text{bar}}\cdot(27.5862-27)\,\text{bar}+9.6287\left(\frac{J}{g\cdot K}\right)$$ **Equation C-36**

$$v_L\left(\frac{L}{kg}\right)=\frac{(1.85205-1.84248)\left(\frac{L}{kg}\right)}{(28-27)\,\text{bar}}\cdot(27.5862-27)\,\text{bar}+1.84248\left(\frac{L}{kg}\right)$$ **Equation C-37**

$$v_g\left(\frac{L}{kg}\right)=\frac{(45.38-47.17)\left(\frac{L}{kg}\right)}{(28-27)\,\text{bar}}\cdot(27.5862-27)\,\text{bar}+47.17\left(\frac{L}{kg}\right)$$ **Equation C-38**

The resulting thermodynamic values used in the calculations are as follows:

Table C-12. Thermodynamics of Initial and Final States Associated with BLEVE.

State	P (bar)	T (°C)	u_L (J/g)	u_g (J/g)	s_L (J/g-K)	s_g (J/g-K)	v_L (L/kg)	v_g (L/kg)
Initial	27.5862	62.22	646.408	398.53	2.4814	9.6195	1.8481	46.12
Final	1.0000	-33.60	195.284	341.72	0.9018	10.8249	1.4664	1137.99

Initially, no vapor is assumed in the vessel, i.e., the vessel is completely filled with liquid ammonia at elevated temperature and pressure. Hence, the mass is

$$m_{L,1}=\frac{(6000\text{ gal})(3.785\text{ L/gal})}{1.8481\,\frac{L}{kg}}=12{,}288\text{ kg}$$ **Equation C-39**

$$m_{g,1}=0\text{ kg}$$ **Equation C-40**

The mass of liquid and vapor at the final state is estimated from the following:

$$m_{L,2}=(1-X_L)m_{L,1}+(1-X_g)m_{g,1}$$ **Equation C-41**

$$m_{g,2}=X_L m_{L,1}+X_g m_{g,1}$$ **Equation C-42**

Where

X_L is the fraction of the initial liquid mass that flashes to vapor

X_g is the fraction of the initial vapor mass that does not condense during the expansion

These fractions are determined with the following:

$$X_L=\frac{s_{L,1}-s_{L,2}}{s_{g,2}-s_{L,2}}=\frac{2.4814-0.90182}{10.8249-0.90182}=0.1592$$ **Equation C-43**

$$X_g = \frac{s_{g,1} - s_{L,2}}{s_{g,2} - s_{L,2}} = \frac{9.6195 - 0.90182}{10.8249 - 0.90182} = 0.8785$$ **Equation C-44**

Where

$S_{L,i}$ is the liquid-specific entropies at state i

Sg,i is vapor-specific entropies at state i

Hence:

The mass of the liquid in the final state calculated using:

$$m_{L,2} = (1 - 0.1592)(12{,}288 \text{ kg}) = 10{,}332 \text{ kg}$$ **Equation C-45**

The mass of the vapor in the final state calculated using:

$$m_{g,2} = (0.1592)(12{,}288 \text{ kg}) = 1{,}956 \text{ kg}$$ **Equation C-46**

And:

For mechanical work only using Equation C-31

$$\Delta U = (m_{g,2}u_{g,2} + m_{L,2}u_{L,2}) - (m_{L,1}u_{L,1})$$ **Equation C-47**

$$\Delta U = \left\{\left[(1956 \text{ kg})\left(341.72 \tfrac{kJ}{kg}\right) + (10{,}332 \text{ kg})\left(195.284 \tfrac{kJ}{kg}\right)\right] - (12{,}288 \text{ kg})\left(646.4078 \tfrac{kJ}{kg}\right)\right\}\frac{1 \text{ MJ}}{1000 \text{ kJ}} = \text{-5,257 MJ}$$

Equation C-48

The energy released from combustion of the vapor component (i.e., 1956 kg) is determined conservatively with the heat of combustion for ammonia (see analysis input) is:

$$\Delta\hat{H}_c = \left(-382.58 \tfrac{\text{kJ}}{\text{mole}}\right)\left(\frac{1 \text{ mole}}{17 \text{ g}}\right)\left(\frac{1000 \text{ g}}{\text{kg}}\right) = \text{-22,500 kJ/kg}$$ **Equation C-49**

It is difficult to identify the exact time when ignition can occur in a flammable liquid BLEVE. However, attempting to realistically, yet conservatively, model the energy release adds energy from the combustion of the vapor portion of the initial state to this expansion energy.

$$\Delta E_c = m \cdot \Delta\hat{H}_c = \left(-22.5 \tfrac{\text{MJ}}{\text{kg}}\right)(1956 \text{ kg}) = \text{-44,012 MJ}$$ **Equation C-50**

Where:

ΔE_c is the energy released due to combustion (kJ)

ΔH_c is the enthalpy of combustion (kJ/kg)

m is the mass of the vapor just before ignition (kg)

Work now becomes

$$W = -\left(\Delta U + \Delta E_c\right) = -(-5{,}257 - 44{,}012) = 49{,}269 MJ$$ **Equation C-51**

Once the work of the expanding gas has been estimated, the dimensionless distance can be determined with:

$$R_s = \theta = R\left(\frac{P_a}{2W}\right)^{1/3} = R\left(\frac{P_0}{E_x}\right)$$ **Equation C-52**

Where

θ is the dimensionless distance
P_a is the ambient pressure (Pa)
W is the calculated work (J)
R is the range or distance from explosion (m)

Combining the mechanical work with the energy released from combustion of the vapor in the final state (just before vessel burst) gives an energy release of 49,269 MJ, with the following results using the Figure C-16 and comparing the results to Table C-13.

Table C-13. Explosion Energy from Mechanical Expansion and Combustion of Initial Vapor Component

R (m)	W (J)	Rs□□□□	P_s (atm)
10.0	4.93E+10	0.10	50.00
50.0	4.93E+10	0.50	1.00
100.0	4.93E+10	1.01	0.38
200.0	4.93E+10	2.02	0.13
300.0	4.93E+10	3.03	0.07
400.0	4.93E+10	4.04	0.05
500.0	4.93E+10	5.05	0.04

The ratio of peak side-on pressure to ambient pressure (P_S/P_a) is a function of θ, and the function is empirically derived for propane BLEVEs and shown in Figure C-16 (CCPS, 1994).

$$\frac{P_s}{P_a} = f(\theta)$$ **Equation C-53**

As the heat of combustion for propane is approximately a factor of 5.8 larger, the results are considered to be conservative for an ammonia BLEVE. Using Figure C-16, the peak side-on pressures (P_s) can be estimated for various distances.

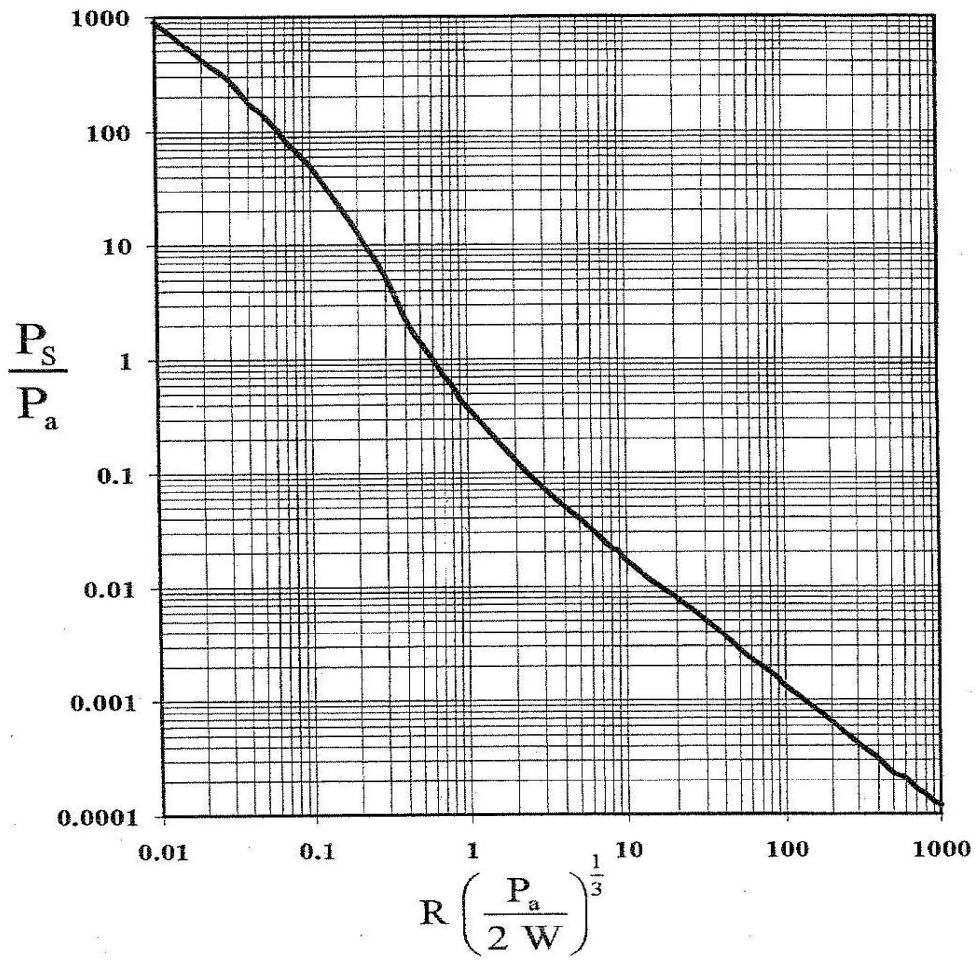


Figure C-16. Dimensionless Overpressure vs Distance Curves for BLEVE Events

The estimate evaluates the overpressure from the expansion, and then re-evaluates the overpressure including the ignition of the initial vapor component, i.e., as the vessel bursts. Using this methodology, the pressure wave can be modeled as it propagates from the source; however, introduction of obstructions in the area can influence the speed of the wave front and the resulting pressure effects.

The blast wave generated by a BLEVE event may cause building damage or personnel injury. Personnel may be injured as a result of the side-on pressure or the reflected pressure. A comparison of the side-on pressure to empirical data is conducted to determine what damage could be expected from the blast.

Thermal Energy Release Due to Fireball

The following approach was presented to the Energy Facility Contractors Group (Roberts, 2000). The model and formulas presented are derived from the methodology presented in *An Improved Model for the Prediction of Radiant Heat from Fireballs* (Martinsen, 1999). The method uses a solid flame model and assumes a spherical ball rising into the air. The time-dependent diameter and height of the fireball and the duration of the fireball are estimated with empirical relationships.

The duration of combustion (td) for the BLEVE fireball is estimated with the following:

The total mass of the ammonia in the vessel previously calculated using Equation C-41 is $m_{L,1}$ = 12,288 kg.

$$t_d = 0.9M_{FB}^{1/4} = 0.9(12{,}288kg)^{1/4} = 9.48\,\text{sec}$$ **Equation C-54**

Where

t_d is the duration of the burn (sec)
M_{FB} is the mass of the released flammable material (kg)
And, $t_d/3$ is 3.16 sec.

The fireball diameter is time-dependent. The fireball has been observed to reach its maximum diameter during the first third of the burn duration. At this point, the fireball tends to rise into the air, while the fireball diameter remains constant until the fireball dissipates. The following equation is used to estimate the fireball diameter during the fireball growth phase:

$$D(t) = 8.664M_{FB}^{1/4}t^{1/3} \qquad \left(0 \le t \le \tfrac{1}{3}t_d\right)$$ **Equation C-55**

Where

D(t) is the diameter of the fireball (m)
M_{FB} is the mass of the released flammable material (kg)
t is the time after the flammable material release (sec)
t_d is the duration of the burn (sec)

So between 3.16 sec and 9.48 sec, the D_{max} is reached for the fireball

$$D_{\max} = 5.8M_{FB}^{1/3} == 5.8(12{,}288\,\text{kg})^{1/3} = 133.8m \qquad \left(\tfrac{1}{3}t_d \le t \le t_d\right)$$ **Equation C-56**

A ground flash radius represents the distance that may be engulfed in flames during the initial development of the BLEVE fireball. This radius can be used to define areas that preclude activities such as refueling and laydown storage. It has been approximated using the following relationship (CCPS, 1999):

The ground flash radius is estimated to be

$$R_{flash} = 0.65D_{\max} = 0.65(133.8\text{ m}) = 87.0m$$ **Equation C-57**

As the fireball heats and expands with less dense hot gases, the center of mass associated with the fireball begins to rise. The height of the center of mass is a function of burn time, which has been estimated from empirical observations (Martinsen, 1999). The fireball has a moment in time where it lifts-off the ground, which can alter hazards associated with the heat flux. The model uses the concept of a fireball rising above the ground, not a column of fire.

The height of the center of the fireball can be determined using Equations C-58 and C-59 (Martinsen, 1999; Roberts, 2000):

$$H_{FB}(t) = \frac{D(t)}{2} \qquad \left(0 \le t \le \tfrac{1}{3} t_d\right)$$

Equation C-58

At the end of the burn time, the height reached by the center of mass is:

$$H_{FB}(t) = \frac{3D_{\max} t}{2t_d} = \frac{3}{2}(133.8\ \text{m}) = 200.8\ \text{m} \qquad \left(\tfrac{1}{3} t_d \le t \le t_d\right)$$

Equation C-59

Where H_{FB} is the height of the fireball center (m)

The radiant heat flux fraction is determined in Roberts (2000). Therefore, the dimensionless radiant heat flux factor is

$$f = 0.27 P_B^{0.32} = 0.27(2.757\ \text{MPa})^{0.32} = 0.3735$$

Equation C-60

Where

f is the radiant heat flux fraction, dimensionless
P_B is the vessel burst pressure (MPa)

The thermal radiation emitted from the surface of the fireball is also time-dependent. The surface emitted heat flux has been estimated from empirical observations (Martinsen, 1999). The fireball surface emitted flux is assumed to be constant during the fireball growth period, and then is assumed to linearly decrease from its maximum value to zero during the last two-thirds of fireball duration.

With ignition, and up to 3.16 sec, the maximum surface emitted thermal flux is

$$E_{\max} = 0.0133 f H_c M_{FB}^{1/12} = (0.0133)(0.3735)\left(22{,}500\ \tfrac{\text{kJ}}{\text{kg}}\right)(12{,}288\text{kg})^{1/12} = 245\ \text{kW/m}^2 \qquad \left(0 \le t \le \tfrac{1}{3} t_d\right)$$

Equation C-61

Where

E_{max} is the maximum surface emitted thermal flux (kW/m^2)
H_c is the net heat of combustion of the flammable material (kJ/kg)
M_{FB} is the mass of the released flammable material (kg)
f is a radiant heat fraction (dimensionless)

Fire research suggests that the maximum surface emitted flux will not exceed some upper limit ranging from 300 to 450 kW/m^2. A value of 400 kW/m^2 is suggested as a limiting value (Martinsen, 1999). Therefore, this value will be used to check as the calculation proceeds.

$$E_S = E_{\max}\left[\frac{3}{2}\left(1 - \frac{t}{t_d}\right)\right] \qquad \left(\tfrac{1}{3} t_d \le t \le t_d\right)$$

Equation C-62

Where E_S is the surface emitted flux (kW/m^2).

The thermal flux incident upon a target object is a function of the geometric view factor between the fireball and the target. The most conservative approach assumes that the target area is normal to the surface of the fireball as the fireball rises into the air. For a target at ground level, a maximum geometric view factor for a spherical emitter is derived as shown in was derived as follows:

$$F(x,t) = \frac{[D(t)]^2}{4\left(H_{FB}^2 + x^2\right)}$$ **Equation C-63**

Where

F(x, t) is the maximum geometric view factor (dimensionless)
x is the distance the target is from the fireball center (m)

The atmospheric transmissivity between the fireball and the target is often assumed to be 1, but it can be estimated from the following equation (CCPS, 1999):

$$\tau(x,t) = 2.02\{P_w X_s\}^{-0.09}$$ **Equation C-64**

Where

τ (x, t) is the atmospheric transmissivity between the fireball and the target (dimensionless)
P_w is the partial pressure of water at ambient temperature (Pa)
X_s is the distance from the flame surface to the target (m)

The atmospheric transmissivity can be re-written as:

$$\tau(x,t) = 2.02\left\{RP_v\left[\sqrt{H_{FB}^2 + x^2} - \frac{D(t)}{2}\right]\right\}^{-0.09}$$ **Equation C-65**

Where

R is the fractional relative humidity
P_V is the vapor pressure of water at ambient temperature (Pa)

The thermal flux at a target is given by the following equation (CCPS, 1999):

$$I_{th}(x,t) = \tau(x,t)F(x,t)E_s(t)$$ **Equation C-66**

Where

I_{th}(x, t) is the thermal flux at a target (kW/m^2)
τ (x, t) is the atmospheric transmissivity between the fireball and the target (dimensionless)
F(x, t) is the maximum geometric view factor (dimensionless)
E_S is the surface emitted flux (kW/m^2)

Personnel injuries and equipment thermal damage resulting from exposure to a BLEVE fireball are dependent upon the thermal dose of the fireball. The dose is best approximated with numerical integration (Roberts, 2000).

$$I_{dose}(x) = \int_{t=0}^{t_d} I_{th}(x,t)dt \approx \sum_{t=0}^{t_d} I_{th}(x,t)\Delta t$$ **Equation C-67**

The integral is obtained with a running integral of integrands taken at small, regular time intervals.

Using the entire ammonia mass (27,034 lbm) to construct a fireball, we find a fireball with a maximum diameter of approximately 178 m (Equation C-55). The ground flash distance, where the flame will reach and possibly lead to subsequent fires and injury, is 87 m (Equation C-57). The duration of the burn is 9.48 seconds (Equation C-54); however, the fireball lifts off after 6.32 seconds. The center of the fireball reaches 201 m into the air (Equation C-58).

The thermal dose varies with distance, so it was calculated using an Excel Spreadsheet and is presented in the following Table C-14 and Figure C-17.

Table C-14. Thermal Dose Associated with BLEVE.

Target Distance (m)	Thermal Dose (kJ/m^2)
25	1042
50	666
75	440
100	304
125	220
150	164
175	127
200	100
225	81
250	67

The thermal dose was determined for 20 equidistant locations from the source to derive a more accurate graphical representation of the data (Figure C-17).

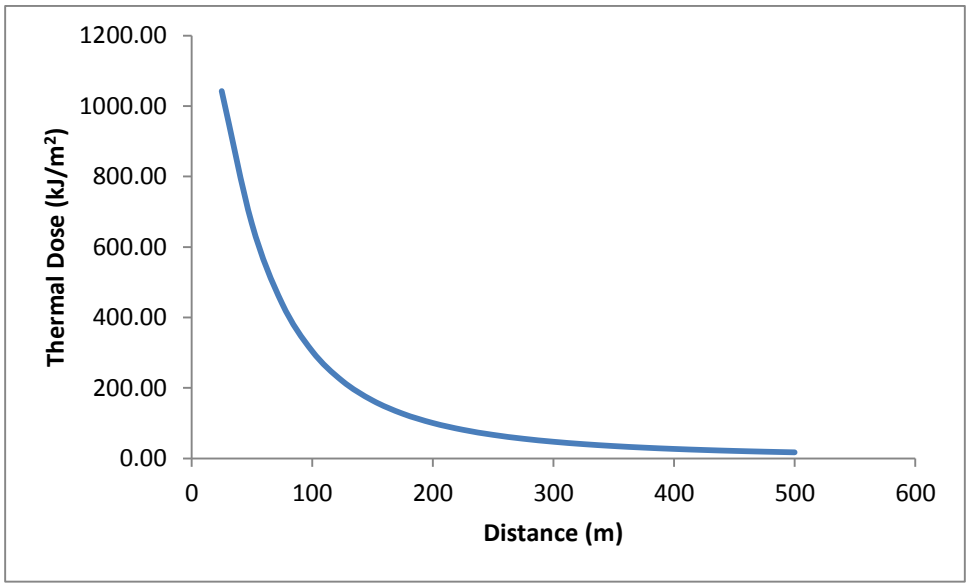


Figure C-17. Thermal Dose from Ammonia BLEVE.

Further comparisons of energy to the description of thermal dose damage (Table C-14) and worker exposure (Table C-10) indicates a potential for the following:

- Ignition of fuel oil around 32 m
- Spontaneous ignition of timber around 42 m
- 50 % fatality for personnel around 67 m
- 1 % fatality for personnel around 115 m
- 2nd degree burns for personnel around 158 m
- Physical pain and superficial skin damage around 200 m

Failure of steel and concrete structures and process equipment due to the thermal radiation is not expected.

The thermal dose is the integral result of the instantaneous thermal radiation. For comparison, the thermal radiation as a function of time during the BLEVE is presented in Figure C-18 for distances of 25 m to 100m.

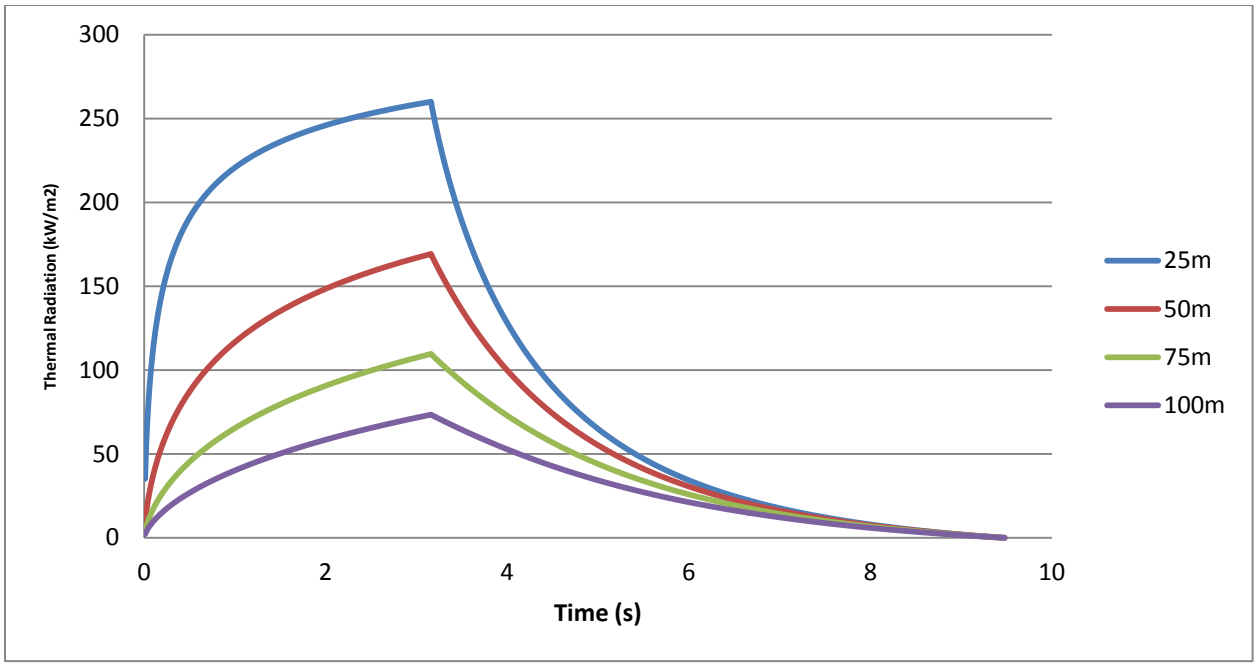


Figure C-18. Thermal Radiation from Ammonia BLEVE.

It is evident that at distances very near the fire ball a target would be subjected to very high thermal radiation for a period of 1-3 seconds. Thermal radiation on the order of 200 kW/m^2 is comparable to the heat flux inside the flaming region of a fire. Intrinsically, very short exposures to a heat flux of this magnitude would cause skin burns and ignition of thermally thin materials (e.g. paper, light fabrics, etc.). It is concluded that a person within this distance of the BLEVE fireball would be subject to extreme burns over much of the body. Also, ignition of flammable liquids would be expected.

Fragment Distance and Impact Energy

About 80 % of vessels that experience catastrophic failure fail with fragments. Empirical and post-accident data indicate that the fragments are not uniformly distributed. The axial direction receives more fragments than from the sides. Approximately 80 % of fragments are found within a range of 300 m; however, it has been found that BLEVEs from smaller Liquified Petroleum Gas (LPG) vessels have a history of greater range (1000 m). Models exist for the numbers and sizes of fragments associated with BLEVEs, but the ammonia vessel capacity (22.7 m^3) falls well below the minimum range of applicability for the models (i.e., 700 m^3) (CCPS, 1989).

Fragments from a BLEVE appear to be similar to metal that has been torn (See Figure 15 of *Comparison of Thermally Coated and Uninsulated Rail Tank Cars Filled with LPG Subjected to a Fire Environment* (Townsend, 1974)). The method discussed in *Shock, Impact and Explosion- Structural Analysis and Design* (Bangash, 2009), considers smaller fragments, which both increases the number of fragments while decreasing the size. The method is useful for estimating the initial velocity for fragments. Equation C-68 uses the size of the explosive charge and the size of the casing to estimate the initial velocity.

$$v_i = 2{,}400\left[1 - \exp\left(-\frac{2Q}{M_C}\right)\right]$$ **Equation C-68**

Where

v_i is the initial velocity (m/s)
Q is the charge weight (kg)
M_c is the weight of the casing (kg)

In addition, Q is based on a high explosive. High explosive is expressed in TNT equivalents, and the following formula is used to determine the charge weight, Q: [Derived from Equation 2.2.1, CCPS, 1989]

$$Q = K\left(\frac{V_{vessel}}{v_L}\right)\Delta H_c\left(YF\right)$$ **Equation C-69**

Where

ΔH_c is the heat of combustion (cal/kg)
V_{vessel} is the vessel volume (m^3)
v_L is the specific volume for the liquid (m^3/kg)
K is a conversion factor relating the energy to TNT equivalents (1 g/1100 cal TNT)
YF is a dimensionless yield factor

Note this determination of charge weight should only be used to estimate the fragment velocity. Almost all gases and vapors do not detonate. As ammonia is not a member of select gases that easily detonate, it is highly unlikely that ammonia will detonate. However, even if ammonia experienced a deflagration-to-detonation transition, such as seen for other flammable gases with geometric conditions favorable to flame front acceleration, it would not achieve the pressures and impulses expected from a condensed phase explosive. The model is based on a condensed phase explosive charge, and as such, the fragment velocity estimate is expected to be conservative.

For a given trajectory, fragments with larger mass travel further than fragments of lighter mass, but larger fragments also experience more drag. The fragment velocity is attenuated in air, depending on the initial fragment velocity, the fragment mass, and the type of fragment. The attenuation of a steel fragment velocity can be estimated with Bangash (2009):

$$v_r = v_i \exp\left(-\frac{0.00456 \cdot r}{\sqrt[3]{m_f}}\right)$$ **Equation C-70**

Where

v_r is the reduced velocity (m/s)
r is the distance (m)
v_i is the initial fragment velocity (m/s)
m_f is the fragment mass (kg)

The mass of the empty ammonia vessel is approximately 11,812 kg. A BLEVE typically shows large fragments, and sometimes the entire vessel is propelled. Since the size of the vessel precluded the use of models to estimate the number of fragments, this calculation focused on determining the potential penetration into concrete and steel of smaller fragments, i.e., 1 g, 10 g, 100 g, and 1 kg. Such fragments impact targets at varying angles and velocities; however, this calculation focuses on the penetration based on velocity only.

Figure C-19 shows the penetration into concrete with a compressive strength of 4000 psi. A 1 kg fragment is predicted to penetrate over 53 cm for short distances from the explosion. The same fragment is predicted to penetrate over 10 cm at distances of 240 m from the explosion.

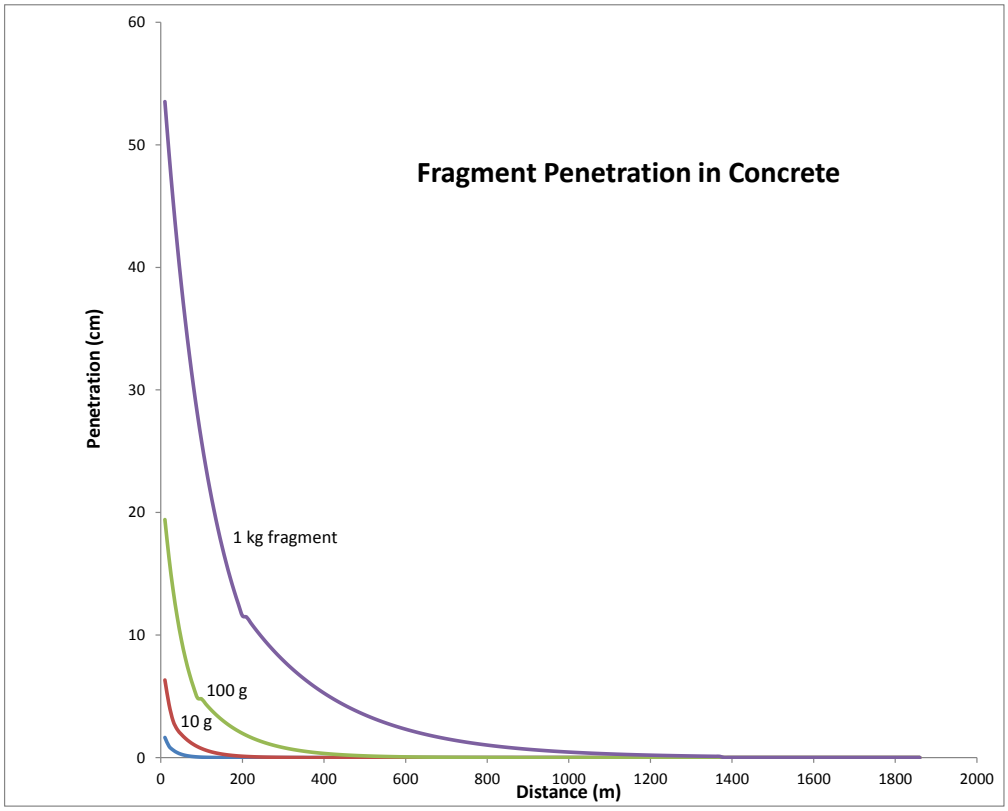


Figure C-19. Fragment Penetration in Concrete.

The depth of penetration, x (inches) can be estimated for fragments penetrating massive concrete by the following two equations (Bangdash, 2009);

$$x = \frac{0.95 m_f^{0.37} v_s^{0.9}}{f_c^{0.25}} \qquad \left(x \le 1.4 m_f^{1/3}\right)$$ **Equation C-71**

$$x = \frac{0.646 m_f^{0.4} v_s^{1.8}}{f_c^{0.55}} + 0.48 m_f^{1/3} \qquad \left(x > 1.4 m_f^{1/3}\right)$$ **Equation C-72**

Where

x is the penetration distance (inches)
m_f is the fragment weight (oz)
V_s is the striking velocity (kfps)
F_c is the concrete compressive strength (ksi)
1.4 $m_f^{1/3}$ is the concrete range limit (inches)

These formulas are converted to the metric system using conversion factors of 6.895 MPa/ksi, 28.34 g/oz, 2.54 cm/in, and 3.2808 ft/m.

$$x = \frac{\left(6.5945 \times 10^{-3}\right) m_f^{0.37} v_s^{0.9}}{f_c^{0.25}} \qquad \left(x \le 1.166 m_f^{1/3}\right)$$ **Equation C-73**

$$x = \frac{\left(4.2079 \times 10^{-5}\right) m_f^{0.4} v_s^{1.8}}{f_c^{0.55}} + 0.40 m_f^{1/3} \qquad \left(x > 1.166 m_f^{1/3}\right)$$ **Equation C-74**

Where
x is the penetration distance (cm)
m_f is the fragment weight (g)
V_s is the striking velocity (m/s)
F_c is the concrete compressive strength (MPa)
1.166 $m_f^{1/3}$ is the concrete range limit (cm)

For penetration of steel, the methodology found in Section 6.3.2.2 of DOE-STD-3014-2006, *Accident Analysis for Aircraft Crash into Hazardous Facilities,* is used.

$$y^{1.5} = \frac{0.5 M V^2}{17{,}400 \cdot K_S D^{1.5}}$$ **Equation C-75**

Where
y is the predicted thickness to just perforate a steel plate (in)
M is the missile mass, i.e., W/g (lb_f-sec^2/ft)
V is the missile impact velocity (ft/sec)
K is a constant depending on the grade of steel (typically 1)
D is the missile diameter (in)

Converting this equation to metric results in:

$$y = \left(4.94091 \times 10^{-3}\right) [M]^{2/3} [V]^{4/3} [D]^{-1}$$ **Equation C-76**

Where
y is the predicted thickness to just perforate a steel plate (cm)
M is the missile mass (kg)
V is the missile impact velocity (m/sec)
D is the missile diameter (cm)

This is a widely accepted formula for predicting penetration of steel targets from the Ballistic Research Laboratory. It should be noted that the range of test data parameters used in developing this formula and their scope of applicability are not defined. However, the formula is independent of target size or support conditions. It should be used only to predict local perforation of steel structures by small rigid missiles. To prevent perforation of steel targets, the minimum thickness should be considered to be greater than 1.25 y (Section 6.3.2.2, DOE-STD-3014-2006).

Figure C-20 shows the penetration into steel. The curves are based on equidistant data points of 10 m to a distance where the penetration did not reach the de minimis value of 0.073 cm.

An oblong fragment of 1 kg should be considered capable of penetrating over 26 cm of steel at short distances from the explosion. The same fragment is predicted to penetrate 0.073 cm at distances of 980m or approximately 1 km from the explosion.

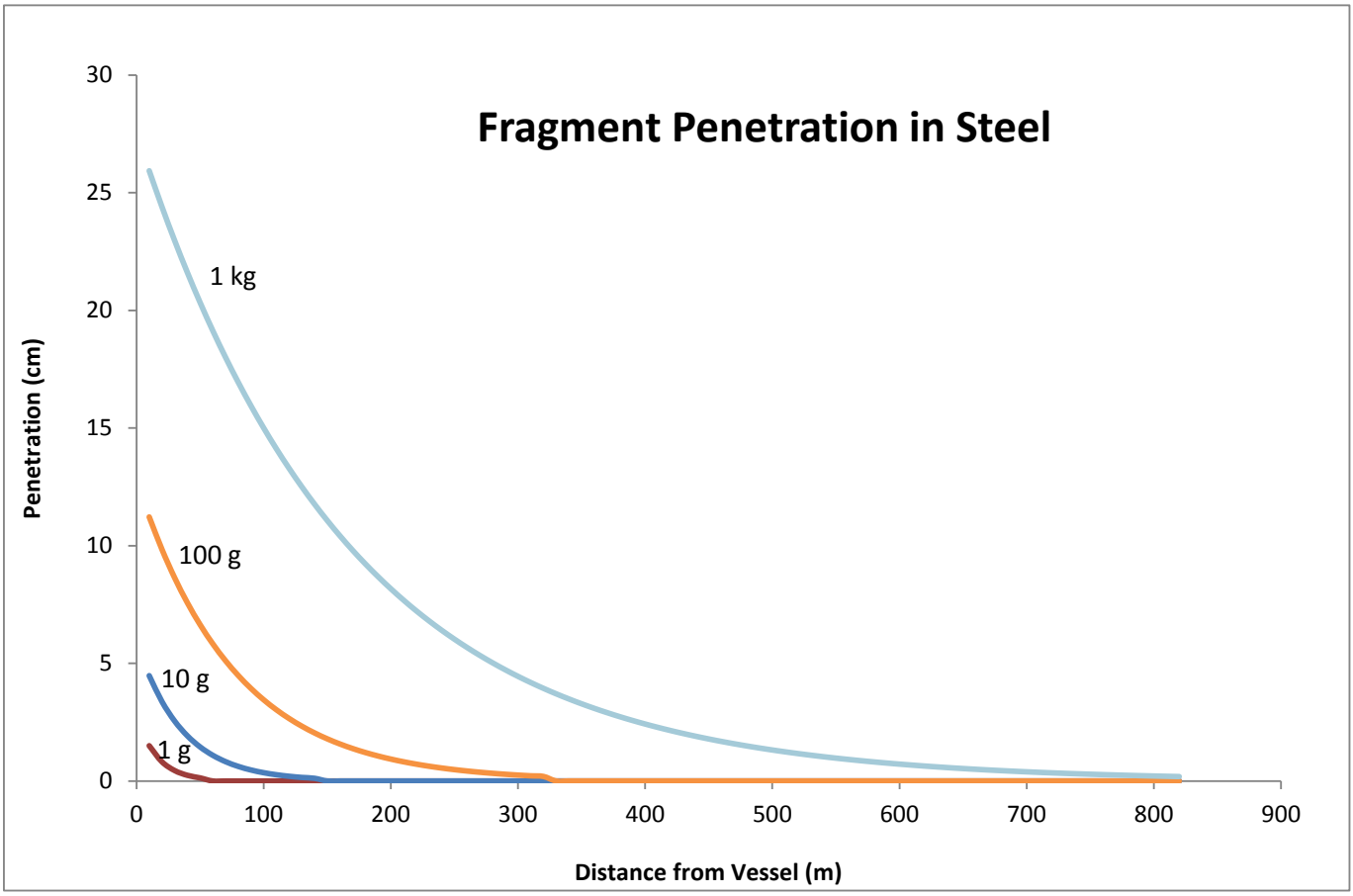


Figure C-20. Fragment Penetration into Steel.

Comparison to Known Damage

The energy from the explosion causes damage that is usually evaluated by comparing to empirically derived values. Table C-15 shows several values for damage expected from overpressure.

Table C-15. Known Damage from Exposure to Overpressure.

Overpressure		Expected Damage
psig	atm	
1.0-2.0	0.068-0.136	Corrugated metal panels buckle and fail Wood panels on standard houses blown in
2.0-3.0	0.136-2.041	Concrete or cinder block walls, not reinforced, shattered
3.0	0.204	Steel building distorted and pulled away from foundation
5.0	0.340	Wooden utility poles snap
4.0-7.0	0.272-0.476	Major damage on steel construction objects
5.8-8.7	0.394-0.592	Heavy damage on reinforced concrete buildings
300	20.4	Cratering
References: (1) K-H, 2001, (2) OGP, 2010, (3) Chang, 2010		

Table C-9 shows several values for material damage expected from thermal radiation. The referenced values shown in Table C-9 were converted to thermal dose values. This is achieved by instituting an equal-area assumption (Assumption 3), i.e. thermal radiation multiplied by time. The values to use for comparison are shown in Table C-9.

Thermal dose values pertinent to worker safety are shown in C-10.

For comparison of penetration into steel, a de minimis value of 0.7295 mm is used for calculating required distances of target from source. This value is based on 20 gauge standard steel, which is 0.0359 in (0.91186 mm) thick. The acceptable penetration distance must be reduced by a factor of 1.25 to assure confidence that there is no perforation (Section 6.3.2.2, DOE-STD-3014-2006). Rounding this value up to three significant figures gives 0.730 mm or 0.073 cm.

Results and Conclusions

Other Effects

DOE-STD-3014-2006 states if a structure has an earth cover exceeding 1.2 times the penetration depth calculated by assuming a rigid missile, the missile should be assumed not to directly impact the structure. Buried concrete structures buried less than approximately 65 cm (or 2.1 ft.) should be expected to be vulnerable to damage from the 1 kg fragment. Buried steel piping less than approximately 31 cm (or 1 ft.) should be expected to be vulnerable to damage from the 1 kg fragment. Other failure modes for the buried pipeline should be expected from cratering and shock waves. Cratering is modeled to extend out to about 14 m.

The associated shock wave will dissipate in the ground and surrounding structures. It should be anticipated that the BLEVE will probably affect any local seismic instrumentation and associated interlocks.

Further research should be conducted into fragmentation and fragment penetration, as well as into the hazards associated with jet flames from a breached ammonia storage vessel.

Uncertainty and Conservatisms

While there are two ammonia vessels, a BLEVE event would most likely involve a single vessel, unless the event could simultaneously fail both vessels and ignite both vessel contents. A more realistic event would be one BLEVE leading to another subsequent BLEVE, which was seen in the San Juanico Disaster of 1984. Since both vessels are of the same construction, it is expected that this calculation will apply to a BLEVE originating from either vessel.

From a survey of 50 notable BLEVEs from around the world over a 60-year span (1926 to 1986), it has been found that most flame-induced liquefied gas BLEVEs occurred when there is approximately one-half to three-fourths of the liquid remaining in the container (Peterson, 2002). Some firefighters who have survived BLEVEs have commented how they have been cooled by the rapid evaporation of liquids that have passed in their vicinity (Peterson, 2002). The calculation presented here uses a completely full vessel and experiences complete combustion for a conservative approach.

While conservatism is introduced by using these models and by choosing realistically conservative parameters, the models are empirical, and as such are susceptible to new data and model perspectives causing different results. The models are not laws of physics. Additional modeling could be performed to account for other phenomena. For instance, this calculation models a spherical, rising BLEVE. If a container fails rapidly, it will produce spherical fireballs. However, if the liquid within the vessel is relatively cool, a large ground fire may result (Peterson, 2002). Currently there is no model available to account for rates of release.

The modeling does not take into account atmospheric effects. It is expected that high winds would drive the fireball away from the point of ignition, but it is also expected that high winds would disperse concentrations and heat quicker.

Consequence Comparison

The energy from the explosion causes damage that is usually evaluated by comparing to empirically derived values. Table C-15 shows several values for damage expected from overpressure. Table C-9 shows several values for material damage expected from thermal radiation. Thermal dose values pertinent to worker safety are shown in Table C-10.

As discussed above, for comparison of penetration into steel, a de minimis value of 0.7295 mm is used for calculating required distances of target from source. This value is based on 20 gauge standard steel, which is 0.0359 in (0.91186 mm) thick. The acceptable penetration distance must be reduced by a factor of 1.25 to assure confidence that there is no perforation [Section 6.3.2.2, DOE-STD-3014-2006, *Accident Analysis for Aircraft Crash into Hazardous Facilities*]. Rounding this value up to three significant figures gives 0.730 mm or 0.073 cm.

APPENDIX D ANALYSIS OF CHEMICAL REACTIONS

Several specific chemical reactions have been demonstrated to be of concern in nuclear materials processing and waste management. These are discussed briefly in this section.

D.1 ORGANIC-BASED ION EXCHANGE RESIN REACTION

D.1.1 REACTIONS OF NITRIC ACID WITH ORGANIC MATERIALS

Nitric acid, in addition to being a strong acid, is a powerful oxidant when concentrated. It "reacts violently with many organic compounds, for example turpentine, charcoal, and charred sawdust. The concentrated acid may react explosively with ethanol. Nitric acid is used with certain organics, such as furfuyl alcohol and aniline, as rocket propellant" (Clarke and Mazzafro, 1996). The explosive properties of such reactions are aggravated by the production of gaseous reaction products, including steam, carbon dioxide, and nitrogen oxides. The concentrated acid can induce nitration in many organic compounds, including both aromatic and aliphatic hydrocarbons, and the products may be unstable to shock or heat.

The nitrating reaction of concentrated HNO_3 with organic materials proceeds by one of two mechanisms. With aromatic compounds and alcohols, the reaction is believed to involve the ion NO_2^+, produced by the equilibrium

$$2\ HNO_3 \Longleftrightarrow NO_2^+ + H_2NO_3- + H_2O \qquad \textbf{Equation D-1}$$

From the principles of mass action, it is evident that in strong acid this equilibrium is shifted to the right. In dilute nitric acid, this equilibrium is shifted to the left and the rate of nitration is negligible. The addition of sulfuric acid favors the nitrating reaction, and sulfuric acid is used for this purpose in the chemical industry.

The second mechanism, which leads to the nitration of aliphatic hydrocarbons, involves reaction of the NO2 radical. This normally occurs only with concentrated acid at very high temperatures. However, ionizing radiation produces this radical in nitrate solutions (Hyder, 1967), making such reactions possible at ordinary temperatures.

D.1.2 COMPOSITION AND REACTIONS OF ION EXCHANGE RESINS

Synthetic ion exchange resins are made in many types, and used for a wide variety of industrial purposes. Those used in nuclear separations processes are primarily of two types: cation exchange resins, and strong base anion exchange resins. Both cation and anion exchange resins are typically composed of polystyrene with active sites chemically bound to the aromatic rings. Cation resins typically contain sulfonic acid groups, which carry a negative charge and bind the positively charged cations through electrostatic forces. The active sites in anion resins are quaternary amine groups, which take on a positive charge that need to be neutralized by a negative ion. Other active groups, such as chelating agents, are sometimes present in resins used for specialized purposes, such as concentrating samples for chemical or radiochemical analysis. Full characterization of ion exchange resins requires specifying resin bead sizes and the extent of cross-linking. Small resin particles permit more rapid exchange, but offer greater resistance to flow. Development of macroreticular resins, which contain large channels that facilitate diffusion, has enabled improved sorption and desorption kinetics. The extent of cross-linking determines the rigidity of resins, and their tendency to shrink and swell as the solution composition varies.

D.1.3 CHEMICAL DEGRADATION OF ION EXCHANGE RESINS

Both strongly basic anion and cation resins are quite stable in neutral and moderately acid aqueous solution at ordinary ambient temperatures. Strong-base anion resins are typically used for plutonium and neptunium separations at nitric acid concentrations in the range of 6 to 8 molar (M). Chemical degradation of the resin is unimportant under these conditions. However, at higher acidities there is an increasing likelihood of reaction between the nitric acid and the amine groups that give the resin its character. The rate of nitric acid reaction with the resin also increases with temperature. Acidity control and low temperatures are therefore important safety factors. For example, at the Savannah River Site, column temperatures during anion exchange processing of plutonium are limited to a maximum of 60 °C, and the nitric acid concentration is held below 9 M. Temperature control becomes especially important when processing highly radioactive alpha-emitting isotopes, such as Plutonium-238 or Americium-241. In these, nearly all the decay heat is released within the ion exchange bed on which they are sorbed.

A number of incidents have occurred in the chemical process industry when weak-base anion resins were exposed to nitric acid. A review has recommended that nitric acid not be used with these resins, as they are apparently more sensitive to attack by nitric acid than the strong-base resins (Calmon, 1980). Calmon also recommends that the presence of ions such as copper, which may catalyze resin decomposition, should be excluded from processes involving nitric acid and resins.

D.1.4 RADIATION EFFECTS ON ION EXCHANGE RESINS

Like all organic material, synthetic ion exchange resins are degraded by ionizing radiation. Although aromatic compounds are less vulnerable to radiation degradation than aliphatic compounds, ionizing radiation can still break chemical bonds within the ring and elsewhere in the resin. Additionally, free radicals formed by radiolysis of water in the resin bed can remove bound hydrogen or attach to the resin. Substituent groups may be removed, and the resin backbone may cross-link. The extensive literature on radiolysis of ion exchange resins has been reviewed by Pillay (1986). Again, the highest radiation dose rates are associated with short-lived alpha-emitting isotopes, which release nearly all their radiation into the bed on which they are sorbed.

Empirical relationships have been developed to establish the maximum radiation dose that a resin can tolerate. For very radioactive material, such as Curium-244, only a single use of a given resin batch may be allowed. For less radioactive material, such as Plutonium-239 or Neptunium-237, repeated use over a long period is allowable. At the Savannah River Site, the maximum allowable dose to anion resin is 108 rad (106 Sv). Generally, the effectiveness of the resin as a separations medium begins to degrade before nitration makes the resin itself a reaction hazard. However, the handling of spent resins should take into account the possibility of radiation-induced nitration, which makes the resin more flammable and more easily subject to chemical degradation.

D.1.5 INCIDENTS INVOLVING CHEMICAL REACTIONS OF RESINS

A number of events, including vessel rupture, fire, and explosion, have occurred in ion exchange equipment exposed to nitric acid. Calmon (1980) has reviewed 14 events occurring prior to 1980, including 8 in nuclear processing operations. Pillay (1986) cites 13 articles dealing with incidents in the nuclear industry, including those cited by Calmon. Several of these incidents were reviewed by Miles (1969). There has also been at least one serious incident in Russia that has not been described in western literature. It was informally reported during bilateral meetings on safety at Hanford in 1993.

Cation resin is considered less vulnerable to degradation than anion resin. However, a major incident in 1976 (ERDA-76, 1976) involved the explosion of a cation column at Hanford that had been loaded with more than 100 g americium, and allowed to stand for more than five months as the result of a plant shutdown. The resin was Dowex 50, 8 percent cross-linked, and the liquid phase was 7 M nitric acid. The column was 6-in. schedule 10 stainless steel pipe. On resumption of work, the column pressurized and burst violently, causing considerable damage and one serious injury. The resin had been exposed to a high radiation dose from absorbed americium during the outage. It is unclear whether the pressure relief vent was open at the time of the accident.

The Russian incident of 1993 involved an anion column loaded with the highly radioactive isotope Plutonium-238. As the result of a valve leak, the column dried out, and the cooling jacket was unable to maintain the central part of the column at a safe temperature. (Heat transfer through dry resin is poor.) The resin was heated by the radioisotope and reacted with enough violence to burst the column. This operation was in a remote facility, and there was no personal injury. However, cleanup and repair were very difficult.

D.1.6 PRECAUTIONS AGAINST RESIN REACTIONS WITH NITRIC ACID

Precautions against resin reactions are of two types: those that prevent the reaction from occurring, and those that mitigate the results.

Precautions to prevent a runaway reaction include temperature control, acid concentration control, and providing adequate cooling. Because most of the heat transfer within a column of resin involves the aqueous phase, it is important that the column not be allowed to dry out. At the Savannah River Site, a maximum flow interruption of 48 h is allowed for processing Pu-239, and a maximum interruption of 15 min is allowed when processing Pu-238. Maintaining flow carries away heat, and helps prevent the formation of bubbles in the resin bed. As previously indicated, maximum values for radiation doses (108 rad), nitric acid concentration (9 M) and temperature (60 °C) are also imposed. The values chosen were based on experience and on the results of laboratory studies of the materials and reactions.

Another method of prevention is to use resins less susceptible to these phenomena. For new resins or processes it is important to determine the reactivity of the system using techniques such as thermogravimetric analysis, differential thermal analysis, and differential scanning calorimetry.

Mitigation primarily takes the form of venting. The design of vents should take into account measured reaction rates and the corresponding gas generation. Design is important; vents should be of the “ever open” type wherever possible. Where this is not possible, as in high-pressure separations systems, careful analysis of the system and control of operating parameters is important to ensure safe operation.

D.2 RED OIL REACTION

D.2.1 BACKGROUND AND CONCERNS

There have been several reported incidents of damage in the nuclear industry as the result of high-temperature reactions between TBP and nitric acid or nitrates. The most recent was the damaging explosion at the Tomsk-7 nuclear fuel reprocessing plant in Russia during April 1993 (Hyder et. al., 1996; Gilbert et. al., 1993). In addition, at least four incidents in North American plants have been attributed to such reactions. Two of these were at the Savannah River Site. One other incident in the Soviet Union has been informally reported.

Damaging incidents occurred at Hanford and the Savannah River Site in 1953 (Colven et. al., 1953; Campbell and Mailen 1998). In each case, TBP solution was inadvertently allowed to enter an evaporator in which a nitrate solution was being concentrated at a relatively high temperature. The damage at Hanford was minor; however, the unit at the Savannah River Site was destroyed by explosion. Temperature controls were established by the two sites following investigations of these incidents, and these have successfully prevented any recurrence within the DOE complex. However, an incident that damaged a Canadian evaporator in 1980 appears to have been caused by a nitrate-TBP reaction (Tanaka, 1994).

A damaging incident at the Savannah River Site in 1975 resulted from the accidental introduction of TBP into a vessel in which uranyl nitrate was being calcined (Gray, 1978). In this case, the calciner was adequately vented, but flammable fumes were released to the process room and ignited, producing a fireball and a pressure wave that blew out the lightly constructed walls.

The explosion in the Tomsk-7 plant involved reaction of strong nitric acid with organic material originating from the PUREX solvent extraction process. The organic material was not well characterized but presumably contained TBP and its degradation products. The materials were contacted in a tank that also contained evaporator bottoms (probably still thermally hot). There was no venting or pressure relief until a substantial pressure had been generated in the vessel. During a period of about 100 min, an accelerating reaction occurred that overwhelmed the pressure relief and finally burst the vessel. Substantial damage to the building was done by the resulting pressure wave and/or ignition of flammable gases released from the vessel.

Investigations of the above incidents have produced much of the available information on TBP-nitrate reactions.

Hyder (1996) summarized investigations regarding TBP-nitrate reactions and provided an interpretation of the experimental results and their pertinence to past incidents. Experimental studies were conducted at the Savannah River Site by Nichols in the 1950s (Colven et. al., 1953) and by a team under Harmon in the middle 1970s (Harmon et. al., 1976). Other investigations have been made at Hanford (Wagner, 1953; Watkins and Gordon, 1993), by the DuPont Engineering Department (Hyder, 1996), and in Russia (Vladimirova et. al., 1991). Additional studies have been conducted at the Savannah River Site and Los Alamos (Hyder, 1994; Davis et. al., 1966; Smith and Cavin, 1994; Fauske, 1994).

The Defense Nuclear Facilities Safety Board issued a technical report on red oil hazards and explosions, DNFSB/TECH-33**,** *Control of Red Oil Explosions in Defense Nuclear Facilities 2003*. It is an assessment of the potential for a red oil explosion in the DOE defense nuclear facilities complex for the year 2003. This reference describes the connection between the process of solvent extraction and red oil production,

identifies the types of process equipment and the necessary materials capable of producing red oil, defines what red oil is and what conditions cause it to decompose in a runaway reaction, summarizes four of the previous red oil events described above, and provides discussions of controls for prevention or mitigation of a red oil explosion (generally categorized as controls for temperature, pressure, mass, and concentration).

Reactions of concern involve oxidation of TBP by nitric acid or nitrates dissolved in it. The oxidant content is typically a small fraction of the amount required for complete oxidation, and most of the TBP is unaffected by this reaction. In sealed tubes the products include principally carbon monoxide, carbon dioxide, water, nitrogen gas, nitrogen oxides (NO and N_2O), and phosphoric acid. Other non-volatile organic materials are also produced, but have not been well characterized. In open vessels, intermediate products such as NO, NO_2, and CO can escape, and the amount of oxidation is less. The heat produced is also much less, as reactions giving these products are less energetic. Heat produced ranges from a measured value of about 100 cal/g in DTA experiments (Watkins and Gordon, 1993), to a calculated value of about 340 cal/g for sealed-tube experiments (Hyder,1994).

At high temperatures (above 130 C), TBP is thermally decomposed to 1-butene and phosphoric acid. This appeasers to be the principal source of flammable gas produced in this reaction. This decomposition is endothermic and requires the oxidation reaction (or some other heat source) to produce the necessary heat (Harmon et. al. 1976; Watkins and Gordon, 1993).

TBP that has been contacted with aqueous solutions will contain some water (Davis et. al., 1966). Savannah River Site experiments (Smith and Cavin, 1994) have shown that heat removal by evaporation is very effective if the water content can be maintained and water vapor removed by proper venting of the atmosphere above the TBP. Hanford experiments have also confirmed this phenomenon (Watkins and Gordon, 1993). Further, the experiments indicate that if the vessel were adequately vented, the transport of water from the underlying aqueous phase to the TBP phase would be sufficient to maintain continuous evaporation and a net cooling.

Also, in a well-vented system, a runaway reaction will not lead to an explosion. Experiments by Fauske (Fauske, 1994) have defined the venting necessary for relief of pressure from a hot TBP and nitric acid reaction.

Formation and thermal decomposition of red oil during unit operations of nuclear fuel cycle process flowsheets is a severe risk. Solvent extraction is a cost effective industrial process to recover, purify, or separate metals. Although several solvents can effectively extract uranium, plutonium, or thorium from acid solutions, the commercially chosen solvent is only TBP. Results of unique experiments on adiabatic thermal decomposition of red oil, red oil equilibrated with excess of 4N nitric acid and 100% TBP equilibrated with excess of 4N nitric acid are discussed (Kumar et. al., 2011). The provision of sufficient vent area in the equipment to avoid closed-vent conditions during worst case scenario needs to be considered (Kumar et. al., 2011).

If sufficient venting of process vessels is available for the quantity of TBP present, failure of the process vessel can be precluded. The basis for determining the proper vent area is the work by Fauske (1994). In this experimental work a number of tests were performed with the Reactive System Screening Tool (RSST) (Creed and Fauske, 1990) and Vent Sizing Package (Fauske and Leung, 1985) calorimeters. These small (10 ml and 110 ml, respectively) calorimeters have been specifically developed for the purpose of studying runaway reactions and determining vent sizes to support safe design and operation in the commercial chemical industry. In open (well-vented) systems, a runaway is much less likely to occur because of release of reactive intermediate gases and evaporative cooling mechanisms. The Fauske

experiments show, that even when runaway is induced in the TBP and nitric acid system, dangerous pressure buildup is prevented with practical vent sizes. In particular, scale up of a test in which TBP was saturated with concentrated (> 70 weight percent) nitric acid indicated pressures should remain low (less than 22 psig) provided the effective vent area was greater than 0.0022 in2/kg of TBP and nitric acid solution. By contrast, identical tests with a closed system, i.e., no vent, was destructive, and an identical test with the vent but with a back pressure of 2 atm. (to simulate the Tomsk control valve opening pressure) resulted in a large pressure with severe bulging of the test vessel

D.2.2 DISCUSSION OF ACCIDENT CONDITIONS

A discussion of the operating or faulted conditions that resulted in each of five historical accidents follows:

- Savannah River Site, TNX Facility, 1953. TBP was inadvertently introduced into an evaporator concentrating uranyl nitrate solution. The evaporation was poorly controlled, and the uranyl nitrate was heated to incipient solidification. Gases from the reacting TBP pressurized and/or ignited and the burst the evaporator.
- Hanford, 1953. This event was very similar to the 1953 event at the Savannah River Site. Pressurization occurred, but it was not sufficient to burst the vessel.
- Savannah River Site. A-Line, 1975. TBP was inadvertently introduced into a heated calciner. Venting allowed gases to escape the primary vessel; however, they were flammable and a deflagration occurred in the process room.
- Port Hope, Ontario, 1980. TBP was inadvertently introduced into a uranyl nitrate evaporator. It appears that the evaporator was operated at a temperature much higher than the normal conservative value. A pressure pulse damaged the upper part of the unit.
- Tomsk-7, Russia, 1993. Concentrated nitric acid was contacted with an undermined but large amount of PUREX organic residues (possibly containing aromatic and cyclic contaminants) in a feed tank. The tank also contained hot, freshly evaporated uranyl nitrate solutions, and was initially unvented. The reaction of nitric acid and the organic material pressurized and destroyed the vessel. The pressure surge, and possibly an external ignition of the released gases, seriously damaged the building.

In four of the five events, TBP was externally heated in the presence of nitrate to a relatively high (though in no case well determined) temperature. In the cases of the evaporator incidents, two errors were involved: introduction of TBP and heating to a high temperature. In the case of the Savannah River Site A-Line calciner, the high temperature was essential to the process, and safety was dependent on keeping TBP out of the unit.

Temperature controls placed on the Savannah River Site, and at other locations, since the 1953 incident have succeeded in avoiding further evaporator incidents at this time. It is noteworthy that the TBP in the calciner incident had passed through an evaporator without incident because of these temperature controls. Replacement of batch calciners by continuous calciners has reduced the potential for inadvertent reaction in the Savannah River Site A-Line. This, along with material control measures, has prevented a recurrence of the 1975 incident.

The Tomsk-7 incident involved the following conditions: contact of strong nitric acid with a large volume of TBP (possibly containing aromatic and cyclic contaminants); a quiescent system with no mixing, hence the organic material need not be in thermal equilibrium with the underlying solution; no venting, and hence no evaporative cooling. In contrast, all similar tanks at the Savannah River Site are vented and mixed. Nitric acid concentrations are limited, as are the volumes of TBP allowed to pass into

such tanks.

D.2.3 APPROACH TO PREVENTING INCIDENTS

The information in the previous sections indicates the set of reactions that take place in an organic-nitric system are exothermic with the reaction rate being a very strong increasing function of temperature. They also indicate the overall reaction rate and energy released is significantly higher in a closed system, as opposed to an open system, because of more energetic intermediate reactions and higher boiling points that results from the increase in constituent partial pressures.

The basic approaches to prevent an uncontrolled reaction include the following:

- Prevent high temperature TBP and nitric acid by ensuring that the cooling mechanisms are capable of removing the heat being generated. The reaction will only run away if the temperature exceeds some critical value (dependent on TBP mass and vessel heat removal mechanisms) above which the rate of heat generation exceeds the rate of heat loss. Vessel cooling systems can remove sufficient heat. Vessel agitation systems can ensure sufficient aqueous phase mixing with an organic phase to ensure evaporative cooling. In unagitated vented vessels (evaporators), the transport of water from the underlying aqueous phase to the TBP phase can be sufficient to maintain continuous evaporation and net cooling. This approach is valid for temperatures up to at least 121 C and organic depths to at least 6.2 ft (Smith and Cavin, 1994).
- Maintain the vessel vent areas to reduce constituent partial pressures in the vessel that could feed back to increase energy release rates and limit evaporative cooling. If the mixture is open to the atmosphere, evaporation of water, diluent, and nitric acid is an efficient heat loss mechanism, which will limit the temperature of the mixture to the atmospheric pressure boiling point. Also, adequate venting allows the escape of reactants and intermediates from the reaction mixture, and limits the extent of the reaction. In contrast, a closed, inadequately vented system allows the pressure to increase as gaseous reaction products accumulate, which raises the boiling point, suppresses the heat loss due to evaporation, and retains partially reacted intermediates which can continue to react and generate heat. Process vessels can readily have vents of sufficient area.
- Limit the mass of TBP present. The total amount of heat generated and total amount of gases generated will be proportional to the amount of TBP that is reacted. With limited amounts of TBP, uncontrolled reactions can be accommodated with minimal consequences.

D.2.4 PREVENTIVE MEASURES

The preventive measures that can be employed to prevent TBP from runaway TBP reactions in a processing facility are given below:

- Process vessel ventilation system
- Process room ventilation system
- Process vessel agitation system
- Evaporator maximum temperature interlock with steam heating system
- Liquid level instrumentation and low level interlocks
- Vessel vent areas
- Sampling of vessels for TBP content
- Time between vessel transfers
- Controls to prevent transfer of solvent wash solutions to acidic evaporators
- Procedure requirements to compare specific gravities of feed tank solutions
- Control of TPB mass of various process locations

With potentially large quantities of TBP, sufficient preventive measures should be selected from the above list to ensure the likelihood of uncontrolled reactions in beyond the extremely unlikely likelihood bin.

For small to intermediate quantities of TBP, the approach in the previous section can be used to predict consequences that may be acceptable.

D.3 SOLID FUEL AND OXIDANT (ORGANIC COMPOUND AND REACTION)

D.3.1 BACKGROUND AND CONCERNS

As discussed in Section 4.5, Analysis of Chemical Reactions, nitrated organic compounds are in widespread use as propellants and explosives. The generation or accumulation of such materials in nuclear facilities may present a risk of runaway reaction, fire or explosion. The materials of primary potential concern include organic compounds containing nitrate or nitrite, but also may concern mixtures of organic material and nitric acid. These materials may be solids, liquids, gels, or slurries.

Waste materials are a particular concern. Once a material is set aside as waste, it is easy to ignore, especially if it is kept in a remote tank because of its radioactivity. Such materials may include spent resins, degraded solvents, analytical reagents, lubricants that have been exposed to acid, and the like. In this environment, over a long time, further reactions may occur. For example, the explosion at Tomsk-7, described in Section 4.5.3, Organic Reaction Event, appears to have involved degraded, impure solvent that had been stored for a long time in contact with nitric acid solution in a radioactive environment. The resulting material appears to have been highly reactive toward strong nitric acid.

Another concern is the accumulation of materials in unexpected locations. Decomposition of sulfamic acid during processing has led to the accumulation of ammonium nitrate, a potentially explosive material, in the offgas system. The “red oil” incident in the Savannah River Site A-Line involved a situation in which, unexpectedly, the organic phase was denser than the aqueous material in the tank with it, and so settled to the bottom. It was then unknowingly drawn off and sent to a drying kettle, where it decomposed into flammable gases.

Dealing with these materials therefore involves locating them, sampling them, and developing safe-handling methods. Each case is likely to be unique. The methods for evaluating the problems are general, however, and have been based on long experience in the chemical industry.

D.3.2 ANALYTICAL AND TEST METHODS

A variety of methods have been developed for characterizing the hazards associated with potentially reactive chemicals. In general, reaction of unstable chemical systems will be initiated or accelerated by heating. The tests therefore generally involve heating of small samples under controlled conditions. Differential thermal analysis (DTA) is important in identifying exothermic processes as a function of temperature. The combination of DTA, thermogravimetry, and analysis of the offgases can provide an adequate description of reactivity in many cases. These techniques are adaptable to contained and shielded facilities. For systems in which venting is provided to control the pressure, the method of Fauske has been widely used in the chemical industry to determine vent sizes. This method was used in evaluating the red oil problem. However, it does not appear to have been applied to contained radioactive facilities. Instrumented bomb calorimetry was also applied in studies of the red oil reaction, but again in nonradioactive facilities.

Where the explosive potential is of concern, tests using small explosive initiators have been developed within the explosive industry. These methods are difficult to adapt to radioactive systems, and have mainly been applied to nonradioactive materials. The potential initiator of an explosion is usually fire or heating, so the methods given above will give an indication of the explosive potential.

D.3.3 PREVENTION AND MITIGATION

Prevention of these reactions first involves locating and characterizing the materials, identification of possible reactive chemicals from references such as *Brethericks' Handbook of Reactive Chemical Hazards* (Urben, 2006), and developing an appropriate handling and storage plan. In some cases it may be possible to destroy the material safely. For handling and storage, temperature control is important. Contact with potentially reactive materials should be prevented. When safety analysis determines that the most likely concern for initiating reaction is an external fire, as is often the case, then measures to prevent such fires can be imposed.

Venting will also be important. Nitrogen oxides from slow reactions should not be allowed to accumulate. These can accelerate nitrate oxidation.

D.4 HYDROXYLAMINE NITRATE

D.4.1 BACKGROUND AND CONCERNS

Hydroxylamine, NH2OH, has been used in the nuclear industry as a reducing agent and in decontaminating solutions. It is used as the nitrate (HAN) or sulfate (HAS) salt in solution. It has the advantage of reducing plutonium smoothly to the trivalent state without creating potential solid waste.

Hydroxylamine is unstable against decomposition in the presence of nitric acid, and this reaction is catalyzed by dissolved iron. The net reaction is:

$$4\ NH_2OH \Longrightarrow 3\ N_2O + 7\ H_2O + 2\ HNO_3 \qquad \textbf{Equation D-2}$$

This reaction occurs more readily at higher nitric acid concentrations. It appears that the formation of nitrous acid is an important element in the mechanism. This reaction, once begun, can accelerate to a dangerous rate, producing great quantities of gas and pressurizing containers. At least seven damaging incidents involving the decomposition of HAN have occurred in DOE facilities. The last of these occurred in May 1997 at the Plutonium Reclamation Facility in Hanford. This section was drawn from a 1998 authoritative report on hydroxylamine nitrate in nuclear facilities, DOE/EH-0555, *Technical Report On Hydroxylamine Nitrate*.

D.4.2 PREVENTION AND MITIGATION

The recommendations in the report by Harlow et al. include the following:

- HAN concentrations should not be allowed to exceed 2 M, and the nitric acid concentration should be less than twice the HAN concentration.
- The long term storage of in-process HAN-nitric acid solutions should be avoided.
- Tankage containing HAN solutions should be evaluated to ensure adequate venting in the event of rapid HAN decomposition.
- In preparing HAN solutions the sequence of mixing is important in avoiding autocatalytic systems.
- Care should be taken to avoid the accumulation of HAN solutions as heels or in process lines.
- Strict procedures should be used to avoid contaminating HAN or its solutions with metal ions.
- HAN solutions should be maintained below 40°C.

The detailed recommendations consider five scenarios and discuss the precautions necessary in each case.

APPENDIX E ADDITIONAL DISCUSSION OF ATMOSPHERIC DISPERSION

Once released into the atmosphere, radiological and toxic chemical emissions are transported in the direction of the wind, diluted by the wind as it stretches out the plume, and diffused by atmospheric turbulence[50] in the horizontal and vertical planes. This atmospheric turbulence consists of random, chaotic air motion in the form of countless whirling eddies. These eddies have a great range of size, from millimeters to tens or even hundreds of meters in diameter, with the smaller eddies being embedded within the larger ones (Richardson, 1927). When a plume of radiological or toxic chemical material is released into the atmosphere, the smaller eddies cause the material to diffuse within the plume, while the larger ones cause the plume to meander, mostly in the horizontal plane. These turbulent eddies are formed by surface frictional effects (mechanical turbulence) and by vertical gradients in both the velocity and the temperature of the air (mechanical turbulence and buoyancy), as discussed below.

A puff or plume that is released at the ground level grows vertically due to vertical diffusion. It reflects vertically from the ground surface and from the top of the mixed layer, which act as vertical boundaries. This is discussed in Section E1.1.

Elevated vent releases can be down-washed by the aerodynamic effects of the building into the cavity region behind the building. If the release is from a stack at a height greater than or equal to 2.5 times the height of an adjacent solid structure (Section 1.3.2 of NRC RG 1.145), it is beyond the structure's aerodynamic influence and will remain elevated. An exception is that under very high wind speed conditions, stack tip downwash can occur, bringing even an elevated release down to ground level.

For puff or plume releases less than 2.5 times the height of an adjacent building, a mixed mode release occurs (Section 2.a of NRC Regulatory Guide 1.111, *Methods of Estimating Atmospheric Transport and Diffusion of Gaseous Effluents in Routine Releases from Light-Water Cooled Reactors*). Mixed mode indicates that a portion of the puff or plume remains elevated and the remainder is down-washed to ground level. The exit velocity serves as an escape velocity vector and the wind speed as a capture velocity vector. The amount of the plume that remains elevated is a function of both exit velocity wind speed.

E.1 GAUSSIAN PLUME MODEL FOR NEUTRALLY BUOYANT PLUMES

Atmospheric and terrestrial processes involved in determining the ultimate fate of a radionuclide or chemical pollutant after it is released to the environment are shown in the Figure E-1.These highly complex interactions of physical phenomena with underlying topography and foliar populations are extremely difficult to describe mathematically. In order to approximate the effects of such phenomena, a Gaussian plume model has found wide application.

[50] Molecular diffusion is much slower than turbulent diffusion in dispersing materials, and much smaller in scale, and thus may be ignored.

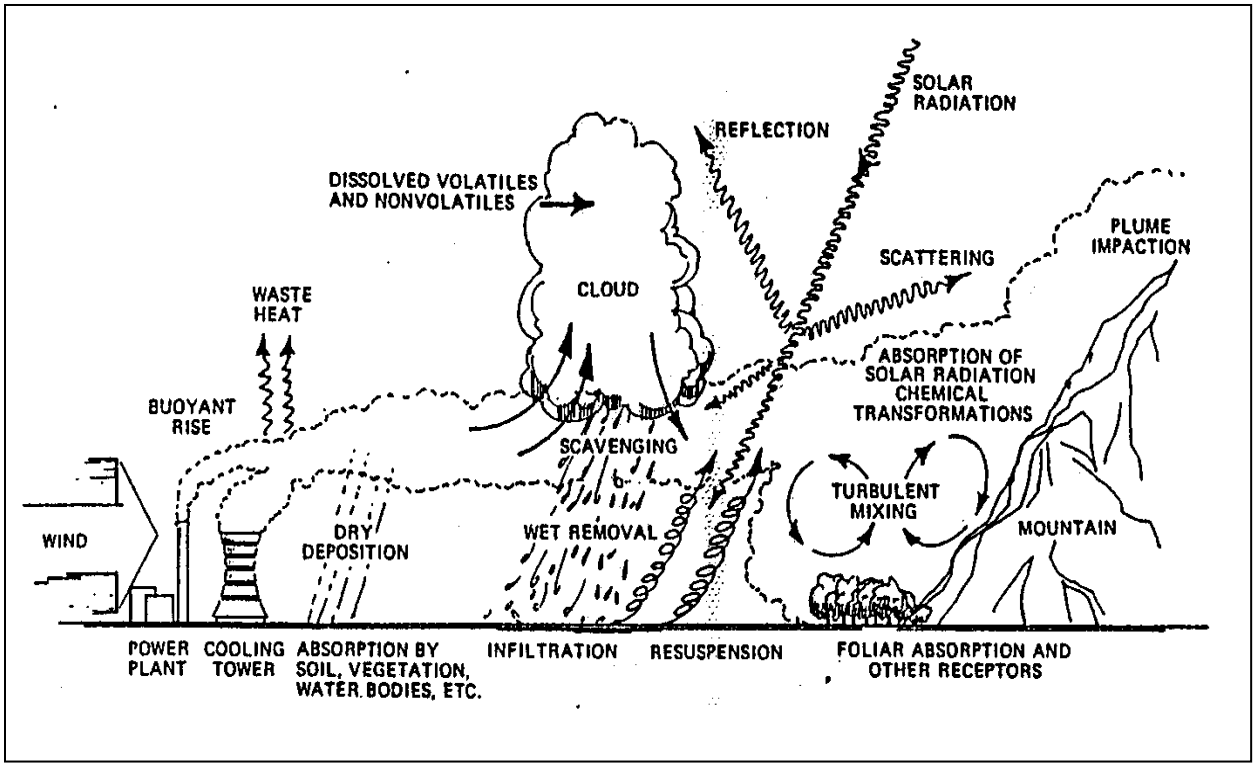


Figure E-1. Atmospheric and terrestrial processes involved in determining the ultimate fate of a radionuclide or chemical pollutant.

The following subsections describe modeling techniques that are used to simulate the effects of these phenomena.

E.1.1 BASIC GAUSSIAN EQUATIONS

The Gaussian approximation of atmospheric dispersion assumes that as a plume is transported downwind, its horizontal expansion is essentially unlimited[51]. Vertical expansion is limited by the earth's surface and aloft under inversion conditions. The downward expansion of the plume stops at the ground, while upward expansion may be stopped if there is a stable layer (a "cap") at the top of the mixed layer. This cap acts as a lid to rising "thermals" of air, thus restricting the range and magnitude of vertical turbulence. The plume is often considered to "reflect" off both the ground and the top of the mixed layer, causing the *vertical* profile to become increasingly uniform as the plume proceeds downwind. For low level mixing heights, multiple reflections can occur from the ground and lid, especially for far-field receptors.

Figure E- (Turner, 1994) illustrates the general shape of a Gaussian plume as released from a stack. The coordinate system typically used in Gaussian equations is shown, in which x is defined as the downwind direction, y is the horizontal cross-wind direction, z is vertical direction, and h is the height of release. The height of the plume after release is H.

[51] Horizontal, or lateral, plume expansion may be somewhat limited by physical barriers, such as buildings and topographic obstacles, but these are normally treated as special cases. Vertical plume expansion can be limited by mixing depth.

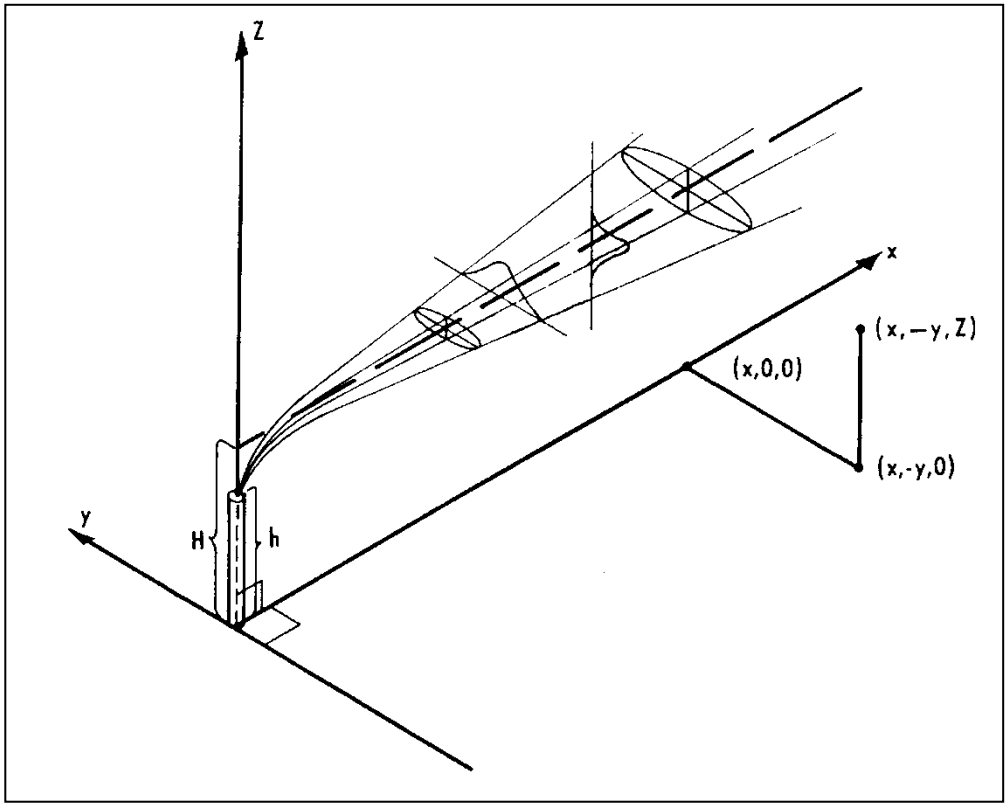


Figure E-2. Coordinate System of Gaussian Plume.

The amount of atmospheric dispersion is usually expressed in terms of χ/Q, where

χ = the concentration of the radionuclides or toxic chemical in air at some downwind (x, y, z) location; this can be either the instantaneous concentration (e.g., Bq/m^3 or g/m^3) or the time-integrated concentration (e.g., Bq-s/m^3 or g-s/m^3), and

Q = the constant rate of radionuclide or toxic chemical release (e.g., Bq/s or g/s), if χ is the instantaneous concentration, or total source strength (e.g., Bq or g), if χ is the time integrated concentration.

The units of χ/Q are s/m^3 whether the instantaneous or time-integrated releases are considered or whether radioactive or chemical releases are being evaluated. Thus, χ/Q is the concentration of the radionuclides or toxic chemical in air at the receptor per unit source rate, or time-integrated concentration per unit source. The actual concentration of the radionuclides or toxic chemical in air (□□□at the receptor is thus the product of χ/Q and the rate of release of the radionuclides or toxic chemical (Q), as determined by the source term calculations from Chapter 5 of this Handbook.

The Gaussian plume model (Slade, 1968), when not constrained in the vertical by the ground or the top of the mixed layer, is expressed as:

$$\frac{\chi(x,y,z,h)}{Q} = \frac{1}{2\pi u \sigma_y \sigma_z} e^{-y^2/2\sigma_y^2} \left[e^{-(z-h)^2/2\sigma_z^2} + e^{-(z+h)^2/2\sigma_z^2} \right] \qquad \textbf{Equation E-1}$$

where

x = downwind distance of the receptor from the point of release,

y = horizontal cross-wind distance of the receptor from the centerline of the plume,

z = distance of the receptor above the ground,

h = height of the plume centerline above the ground (same as H in Figure E-),

σ_y = standard deviation of the horizontal Gaussian distribution (the "half width"),

σ_z = standard deviation of the vertical Gaussian distribution (the "half thickness"),

u = wind speed at a reference height.

The standard measurement height usually is taken to be 10-m since that is the measurement level of winds at First-Order National Weather Service (NWS) stations and the lowest level of measurement at Federal and commercial nuclear facilities. The constant, χ is implicit in a Gaussian distribution, in which the lateral and vertical components each contribute $(2\pi)^{1/2}$. The wind speed, u, enters mathematically from a time integration of the time-dependent form of the Gaussian equation; physically, it represents the initial dilution of the plume caused by the "stretching out" of the plume when it is initially released. Note that the downwind distance x does not appear explicitly in this equation. The x dependence is implicit, as the σy and σz are functions of x only, for a given stability class.

The bracketed term in Eq. E-1 defines the vertical distribution. If the pollutants are reflected from the ground and from the top of the mixed layer, this term must be modified. This is done mathematically by adding multiple mirror source terms. The bracketed term in Eq. E-1 thus is replaced with:

$$\left[e^{-(z-h)^2/2\sigma_z^2} + e^{-(z+h)^2/2\sigma_z^2} + \sum_{n=1}^{N} \left(e^{-(z-h-2nL)^2/2\sigma_z^2} + e^{-(z+h-2nL)^2/2\sigma_z^2} + e^{-(z-h+2nL)^2/2\sigma_z^2} + e^{-(z+h+2nL)^2/2\sigma_z^2} \right) \right] \qquad \textbf{Equation E-2}$$

The term before the summation in Eq. E-2 is the ground reflection component since perfect reflection is assumed. The series of terms after the summation represent multiple reflections from the top of the mixed layer and the ground. L represents the height of the top of the mixed layer and the summation is over the number (N) of reflections to be considered. The contribution of the summation term is minor, especially for distances close to the source and for larger values of L. The higher order terms contribute progressively less and the series is normally terminated after only a few terms. For example, in the MACCS code (Chanin et. al., 1990), the series is terminated at N = 5.

For a ground-level release (h = 0), the first two exponential terms become equivalent. Each of these terms is one when the receptor is at ground level (z = 0). In this case, the "2" in the denominator of Eq. E-1 cancels out with the "2" in the numerator, if the summation term is ignored, as is often done. The maximum concentration occurs at plume centerline (y = 0). Thus, if the summation term is ignored, the Gaussian equation simplifies to:

$$\frac{\chi(x, y = 0, z = 0, h = 0)}{Q} = \frac{1}{\pi u \sigma_y \sigma_z}$$ **Equation E-3**

Strictly speaking, the numerator in the above expression is slightly greater than one because of the contribution of the summation term. Eq. E-3, which is now only a function of downwind distance of the receptor, is often used for the CW and MOI, as plume centerline represents a conservative value.

E.1.2 GAUSSIAN PLUME WIDTHS AND DEPTHS

The horizontal and vertical spread of pollutants within a Gaussian plume is a function of dispersion coefficients, σy and σz, respectively. These dispersion coefficients are standard deviations of the concentration distributions determined from experimental field data at O'Neill, NE in 1956. As representations of plume boundary spread, σy and σz are often referred to as the "half width" and "half thickness", respectively. The most widely used sets of dispersion coefficients have a common empirical basis with field experiments known as Project Prairie Grass that took place on flat grasslands (Haugen 1959). They are found in *Workbook of Atmospheric Dispersion Estimates, An Introduction to Dispersion Modeling* (Turner, 1994) and Slade (1968) and shown in Figure E-2. These curves became known the Pasquill-Gifford (P-G) dispersion curves52, and the set of parameters represented by them are the P-G dispersion coefficients. The field tracer database underlying the empirical curve fits was for distances between 100 m and 1,000 m and thus the curves beyond 1,000 m are dashed because they represent extrapolations. For distances less than about 100 m, these coefficients do not provide a good fit to the observations and the models are generally not considered valid. This influenced the choice of the selected distance for evaluating the exposure to a co-located worker as 100-m.

[52] These curves are sometimes also referred to as the Pasquill-Gifford-Turner (P-G-T) curves, given their publication by Turner in a workbook developed for the EPA (Turner, 1970).

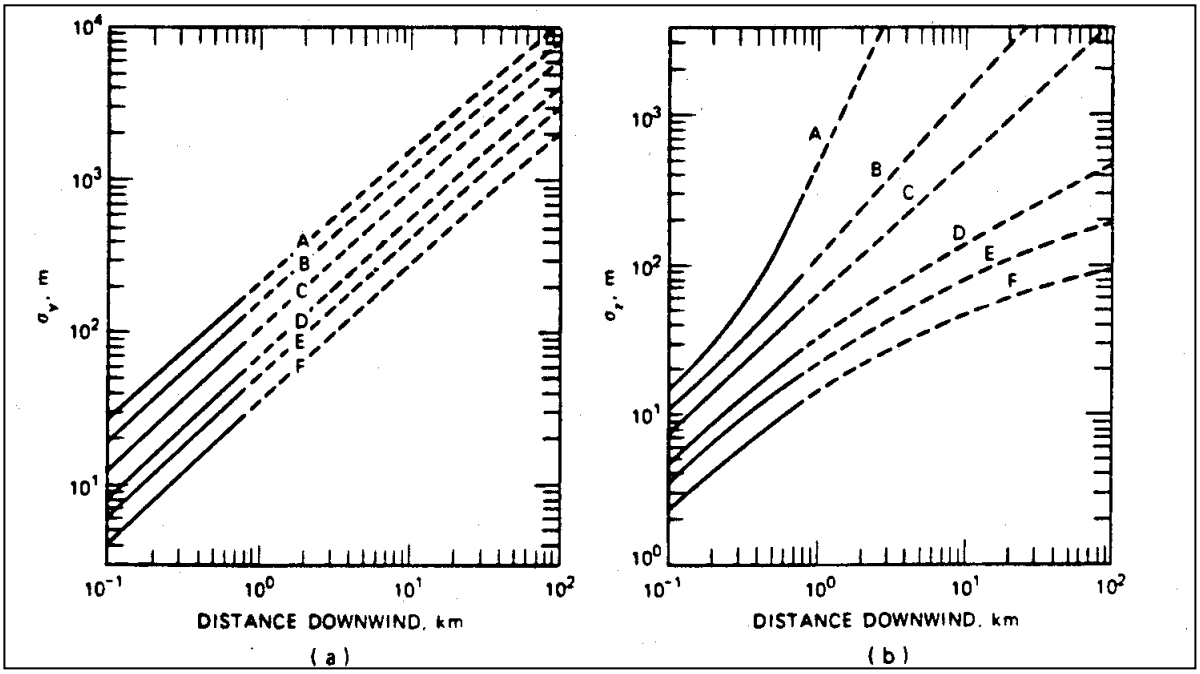


Figure E-2. Variations of Horizontal and Vertical Plume Dimensions with Distance.

For stability class G, the NRC Regulatory Guide 1.145 (NRC, 1982) recommends using a σy that is 2/3 that of stability class F and a σz that is 3/5 that of stability class F, for cases without plume meander or building wake effects. With plume meander and building wake effects this NRC guidance recommends correction factors to σy for classes D – G, especially for low wind speeds. For example, for class G the correction factor varies from a factor of six for wind speeds less than 2 m/s, down to a factor of one (no correction) for wind speeds of 6 m/s and above.

A number of dispersion coefficients sets have been developed over the years. Most sets relate σy andσz to atmospheric stability classes and distance from the source and are based on empirical curve fitting of data that were taken during experiments over flat grassland (Haugen, 1959). One commonly used curve-fitting method is that of *Analytical Expressions for the Vertical and Lateral Dispersion Coefficients in Atmospheric Diffusion* (Tadmor and Gur, 1969), in which each σ is expressed as a power law:

$$\sigma = a\, x^b \qquad \textbf{Equation E-4}$$

where *a* and *b* are empirical constants, given in Table E-2, as used in the MACCS2 code, with the Tadmor-Gur typographical errors corrected; the units of *x* and σ are meters.[53]

Example: For stability class D and a distance of 1000 m, the Tadmor-Gur formulation gives $\sigma_y = 0.1474 \times 1000^{0.9031} = 75.5$ m and $\sigma_z = 0.3 \times 1000^{0.6532-} = 22.2$ m.

[53] In some formulations a third empirical constant, *c*, is added (as in Eq. E-5) but in MACCS2, the *c* term of σ_z has been set to zero for mathematical convenience, which has required an adjustment to the values of *a* and *b*.

Table E-2. Fitting Constants for σ_y and σ_z from Tadmor and Gur as used in MACCS2.

Stability Class	σ_y		σ_z (0.5 to 5 km)		σ_z (5 to 50 km)	
	a_y	b_y	a_z	b_z	a_z	b_z
A	0.3658	0.9031	2.5E-04	2.1250	NA*	NA*
B	0.2751	0.9031	1.9E-03	1.6021	NA*	NA*
C	0.2089	0.9031	0.2	0.8543	0.5742	0.7160
D	0.1474	0.9031	0.3	0.6532	0.9605	0.5409
E	0.1046	0.9031	0.4	0.6021	2.1250	0.3979
F	0.0722	0.9031	0.2	0.6020	2.1820	0.3310

* NA - Not available, so power-law constants for stability class C are applied, per recommendation of the MACCS2 code developer (DOE 2004c).

Eimutis and Konicek developed three sets of power-law expressions of the form shown in Eq. E-5, shown below, to cover three downwind distance regimes: (i) < 100 m, (ii) 100 m to 1000 m, and (iii) > 1000 m (Eimutis, 1972). This parameterization is widely used in NRC dispersion models.

$$\sigma_j = a_j \cdot x^{bj} + c_j \qquad \textbf{Equation E-5}$$

For $j = y$ (horizontal), $b_y = 0.9031$ and $c_y = 0$. The other empirical constants a_j, b_j, and c_j are given in Table E-3.

Table E-3. Fitting Constants for σ_y and σ_z from Eimutis and Konicek.

		ATMOSPHERIC STABILITY CLASS						
	Distance	**A**	**B**	**C**	**D**	**E**	**F**	**G**
a_y	all	0.3658	0.2751	0.2089	0.1471	0.1046	0.0722	0.0481
a_z	< 100 m	0.192	0.156	0.116	0.079	0.063	0.053	0.032
	100 to 1000 m	0.00066	0.0382	0.113	0.222	0.211	0.086	0.052
	>1000 m	0.00024	0.055	0.113	1.26	6.73	18.05	10.83
b_z	< 100 m	0.936	0.922	0.905	0.881	0.871	0.814	0.814
	100 to 1000 m	1.941	1.149	0.911	0.725	0.678	0.74	0.74
	>1000 m	2.094	1.098	0.911	0.516	0.305	0.18	0.18
c_z	< 100 m	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	100 to 1000 m	9.27	3.3	0.0	-1.7	-1.3	-0.35	-0.21
	>1000 m	-9.6	2.0	0.0	-13.0	-34.0	-48.6	-29.2

Example: For stability class D and a distance of 1000 m, the Eimutis-Konicek formulation gives $\sigma_y = 0.1471 \times 1000^{0.9031} = 75.5$ m and $\sigma_z = 0.222 \times 1000^{0.725} - 1.7 = 31.5$ m.

Another commonly used curve-fitting method is that of *Diffusion Estimation for Small Emissions* (Briggs, 1973), for which each σ is expressed as

$$\sigma = a\,x(1 + bx)^{c} \qquad \textbf{Equation E-6}$$

Where *a*, *b*, and *c* are constants, given in Table E-4.

Example: For stability class D, open country, and a distance of 1000 m, the Briggs formulation gives
$\sigma_y = 0.08 \times 1000 \times (1 + 0.0001\times1000)^{½} = 76.3$ m and
$\sigma_z = 0.06 \times 1000 \times (1 + 0.0015\times1000)^{½} = 37.9$ m.

Table E-4. Fitting Constants for σ_y and σ_z from Briggs.

Curve Fitting Constant	ATMOSPHERIC STABILITY CLASS					
	A	B	C	D	E	F
	Open-Country Conditions					
a_y	0.22	0.16	0.11	0.08	0.06	0.04
a_z	0.20	0.12	0.08	0.06	0.03	0.016
b_y	0.0001	0.0001	0.0001	0.0001	0.00001	0.0001
b_z	0	0	0.0002	0.0015	0.0003	0.0003
c_y	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
c_z	1	1	-0.5	-0.5	-1	-1
	Urban Conditions					
a_y	0.32	0.32	0.22	0.16	0.11	0.11
a_z	0.24	0.24	0.20	0.14	0.08	0.08
b_y	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
b_z	0.001	0.001	0	0.0003	0.00015	0.00015
c_y	-0.5	-0.5	-0.5	-0.5	-0.5	-0.5
c_z	0.5	0.5	1	-0.5	-0.5	-0.5

The Tadmor-Gur and Briggs formulations, as well as others, give results that are nearly the same for some distance ranges and stability classes. However, they may differ by a factor of two or more for other distance ranges/stability classes. The coefficients given in the above tables, and in other Gaussian models, are based on fitting curves to observational data of plumes released over flat grassland.

Pacific Northwest National Laboratory (PNNL) evaluated the various sets of dispersion coefficients available with MACCS2 and GENII2 for rural terrain (Napier et. al., 2011). Even though the evaluation was performed for Savannah River Site (SRS) morphology, the general conclusions summarized below are expected to be applicable to other DOE sites.

The Tadmor and Gur set is not recommended for distances less than 500 m. Excluding the Tadmor and Gur set of χ/Q results for less than 500 m, the other parameterizations yield χ/Q results that are essentially indistinguishable in the distances of interest (500 m to about 11 km) at the SRS site. The χ/Q results from the Briggs parameterization begin to diverge from the χ/Q results using the various P-G parameterizations at distances of about 10 km. Beyond 10 km, the Briggs χ/Q results are conservative and even more for E and F stability classes (see Figure A-3 of Napier et. al., 2011). The Briggs parameterization is universally

available with the radiological dispersion toolbox codes and the only available option with HotSpot. The χ/Q results from P-G parameterizations agree with one another out to the plotted distance of 30 km (see Figure A-3 of Napier et. al., 2011).

It is not surprising that the χ/Q results from the P-G parameterizations agree with one another, excluding Tadmor and Gur results for less than 500 m, for the entire range of distances given their common origin of the P-G curves and the Project Prairie Grass data. Moreover, the divergence of the Briggs χ/Q results at distances beyond about 10 km should not invalidate its use at these large distances. The divergence seems to simply reflect the empirical foundation of a larger data set that includes data out to 10 km, compared to 1 km for the P-G data set.

DOE Safety Advisory 2009-05, "Errors in MACCS2 χ/Q Calculations" describes a problem at large distances (greater than 2 km) with the lookup table with MACCS2 versions 1.13.1 and 2.4 (DOE, 2009; Napier et. al., 2011) and it details an approach for avoiding the error. When using this approach the results should be verified to ensure the error was adequately addressed. PNNL evaluated the Safety Advisory approach and found it to be insufficient at addressing the problem (Napier et. al., 2011). This error has been fixed with MACCS2 version 2.6. The PNNL team recommends the use of the power-law approach (Tadmor and Gur dispersion coefficients) that avoids this potential error when using MACCS2 for distances greater than 500 m (Napier et. al., 2011).

Because the Briggs open-country dispersion coefficients are partially based on elevated release data acquired at BNL, consideration may be given to using these for stack releases. The SRS AXAIR code (AXAIR, 1986) uses the Briggs expressions for σ_z, since these expressions were considered more appropriate for stack releases that were common at SRS at the time of its development (Simpkins, 1994; Napier et. al., 2011). Another example is the RISKIND code (ANL/EAIS-6, Rev. 0, 1993), designed for potential radiological consequences from transport of spent nuclear fuel. It uses the Eimutis and Konicek dispersion coefficients if the effective release height is less than or equal to 30 m and the Briggs dispersion coefficients for higher elevated releases (Yuan, 1993).

To more accurately predict dispersion for specific conditions that differ from those represented by the P-G and Briggs open country parameterizations, adjustment factors have been developed to capture enhanced plume spread acting independently in a single direction, such as horizontally for plume meander and vertically for mechanical turbulence caused by surface roughness. These adjustment factors are discussed below, in Section E1.6. Additionally, building wakes introduce enhanced dispersion in the horizontal and vertical directions. Building wake dispersion and related modeling approaches are discussed in more detail in Section E1.6.

E.1.3 WIND SPEED PROFILE WITH HEIGHT

Wind speed varies with height in the Planetary Boundary Layer (PBL). It is often characterized with an equation known as the wind profile power law, which is a relationship between the wind speed at one height, and wind speed at another height. Winds generally increase with height as the frictional effects of the Earth's surface decrease as the distance from the surface increases. When the frictional effects of the surface are no longer felt, the upper boundary of the PBL, and bottom of the free atmosphere, is reached and the winds are termed geostrophic.

The wind profile of the PBL is generally logarithmic in nature and is best approximated using the log wind profile equation that accounts for surface roughness and atmospheric stability. However, the wind profile power law relationship is often used as a substitute for the logarithmic wind profile when surface roughness or stability information is not available.

The wind profile power law relationship is described by:

$$u/u_r = (z/z_r)^{\alpha} \qquad \textbf{Equation E-7}$$

where

u = wind speed (m/s) at height z (m);

u_r = known wind speed at a reference height z_r; and,

α = an empirically derived coefficient that is dependent upon stability of the atmosphere. For neutral stability conditions and a rural environment, α is approximately 1/7, or 0.143. For urban environments it is somewhat larger (for example, see WebMET.com).

The roughness length (z0) affects the wind speed. Roughness length is equivalent to the height above the ground at which the wind speed theoretically becomes zero. The roughness length is related to the frictional effects of the earth's surface on the wind speed. The greater the roughness length magnitude, the greater the frictional effects and resultant mechanical turbulence generated.

A single value for the wind speed is used in the Gaussian plume model equation as shown by Eq. E-1. The wind speed in meteorological data files is generally assumed to correspond to a reference height of 10 m and represents conditions for 10 m and below. The various toolbox models treat the wind speed variability differently, as follows:

- Meteorological data read into the MACCS2 radiological dispersion software is assumed to correspond to a reference height of 10 m. MACCS2 does not adjust the wind speed used in the Gaussian plume equation for the height of release.[54] Thus, wind speed data in the meteorological data files are input directly into Gaussian plume model equation. The use of the 10-m wind speed is conservative in the calculation of the χ/Q value for an elevated release;
- Meteorological data read into the GENII radiological dispersion software is assumed to correspond to a reference height of 10 m. Wind speed data in the meteorological data files are input directly into Gaussian plume model equation for release heights of less than 12 m. For releases of higher elevation, the wind profile power law is used to adjust the wind speed;
- The user specifies the reference height for the meteorological data with HotSpot. With HotSpot designed to read meteorological data files that are formatted for MACCS2, the reference height is typically 10 m. HotSpot adjusts the wind speed for any release height that differs from the reference height. For release heights of 2 m or less (ground level release), the wind speed is calculated from the wind profile power law using a 2-m height. The user can disable the wind speed adjustment by specifying a reference height of 2 m for the meteorological data (Homann, 2010). This allows HotSpot to model ground-level release using the wind speed data directly from the meteorological data files in a way consistent with MACCS2 and GENII (Homann, 2010).

[54] The algorithm in MACCS2 for determining the plume rise of a buoyant release does make use of wind speed correction with height, but this is the only place where MACCS2 accounts for wind speed variability with height.

Unrealistically high estimates of χ/Q can be calculated under calm wind conditions, a result of the placement of wind speed in the denominator of the Gaussian plume model equation. For site-specific monitoring, the EPA recommends using a wind speed of 0.5 m/s for a "calm" wind, and cautions against overly conservative model predictions with wind speeds less than 1 m/s (EPA, 2000). DOE-STD-3009-2014 requires the use of 1.0 m/s as the minimum wind speed when using one of the Central Registry toolbox codes. MACCS2 substitutes a value of 0.5 m/s for the wind speed whenever it reads a wind speed value of less than 0.5 m/s from a meteorological data file, but this is allowed by DOE-STD-3009-2014 as the 0.5 m/s is a fixed part of the code. GENII allows the user to set threshold value through the input for the maximum wind speed for calm. HOTSPOT considers wind speeds down to 0.1 m/s and also considers a G Stability class. However, the analyst should set calm wind speeds to 0.5 m/sec unless there is sufficient justification to reducing it to a lower value.

Figure E-5A illustrates an important limitation of the Gaussian plume model of its tendency to overpredict concentrations at the lower end of a range of representative wind speeds (McGuire, et al., 2007). The figure shows the ratios of normalized concentrations (χ/Q) predicted in building wakes to observed concentration normalized to actual release rate as a function of wind speed. If the errors in the predicted values were associated with the wake, they would increase with wind speed. The authors observed that the overprediction (ratio >1.0) is largest and more numerous at very low speeds and decrease with increasing wind speed indicates that the problem is underestimation of dispersion in low wind speeds. The authors concluded that their original premise that the enhanced dispersion was due to building wakes was incorrect. Instead, the apparent enhanced dispersion noted in the vicinity of buildings at low wind speeds in wake dispersion experiments is caused by underestimation of dispersion by the basic dispersion algorithms rather than by increased turbulence in the vicinity of buildings.

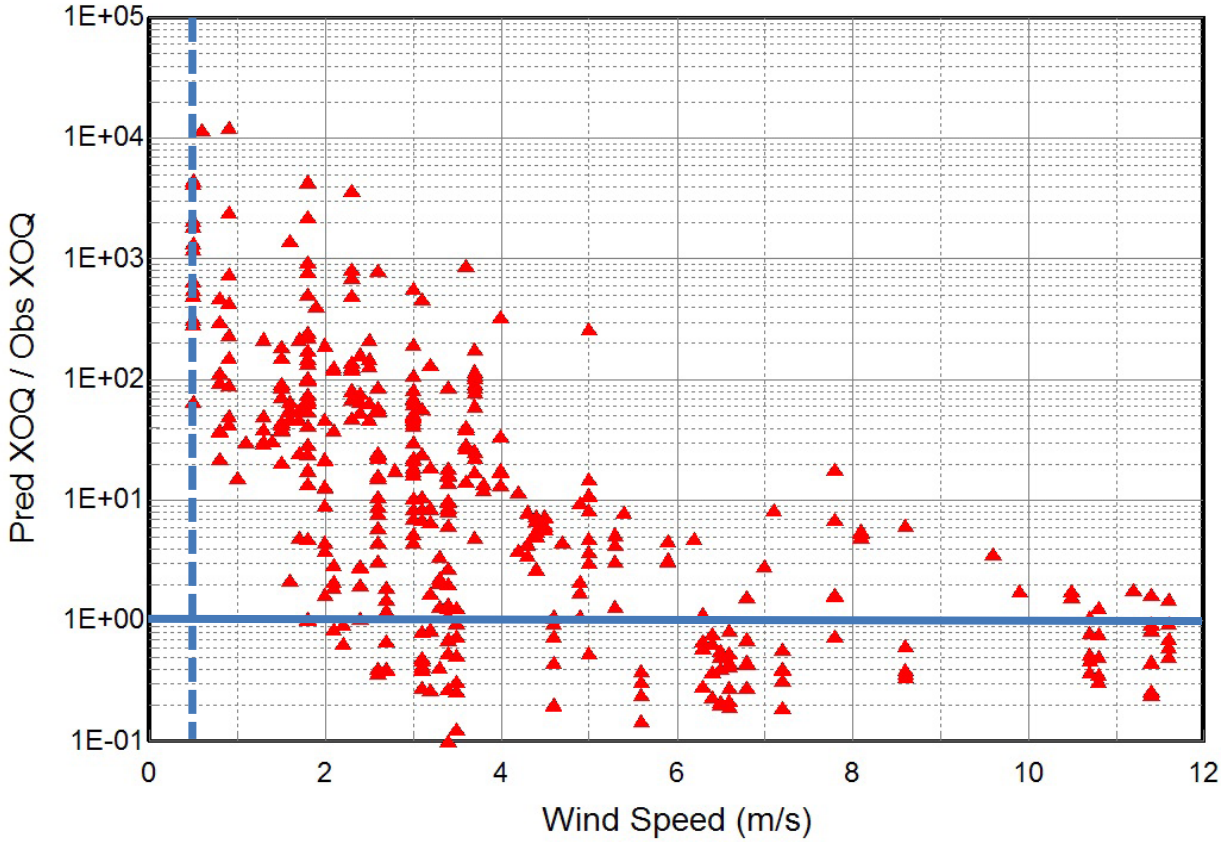


Figure E-4. Ratios of predicted concentrations in wakes by a model without wake correction to observed concentrations as a function of wind speed (based on McGuire et al., 2007). Ratios above solid line (Predicted/Observed = 1) are over-predicting the concentration.

E.1.4 MIXING LAYER HEIGHT

For an evaluation of χ/Q that includes reflections from the ground and the top of the mixing layer, a knowledge of the height of the top of the mixing layer at the site is required. The atmospheric mixed layer is a zone having nearly constant potential temperature and specific humidity with height. Mixing height is the height above which relatively vigorous vertical mixing essentially stops; the layer from the ground to mixing height (mixing depth) is where vigorous vertical mixing occurs. Low mixing heights are related to a meteorological circumstance where air is generally stagnant with very little vertical motion and where radiological and toxic chemical emissions are usually trapped in a narrow layer near the ground surface. Under very stable conditions (F or G stability), the temperature inversion that is common to this stability class is typical of a low mixing height. Correspondingly, high mixing heights allow vigorous vertical mixing within a deep layer of the atmosphere and accordingly a good dispersion capacity.

Mixing heights can be used to estimate how far plumes rise in the vertical. The actual rise of a plume, however, considers complex interactions between atmospheric stability, wind shear, and heat release rate (HRR), density differences between the plume and ambient air, and radiant heat loss. Accordingly, an estimate of mixing height provides only an initial estimate of plume height, but with respect to DSAs, it is sufficient.

Mixing height varies throughout the day and throughout the seasons, since it is directly related to the amount of insolation that reaches the ground level. Mixing heights are usually lowest late at night or early morning and highest during mid- to late-afternoon. Average morning mixing heights range from 300 m to over 900 m above ground level (Holzworth, 1972) for many locations in the United States. The highest morning mixing heights occur in coastal areas that are influenced by moist marine air and cloudiness that inhibit radiation cooling at night. Average afternoon mixing heights are typically higher than morning mixing heights and vary from less than 600 m to over 1400 m above ground level. The lowest afternoon mixing heights occur during winter and along coastal locations. Mixing heights vary considerably between locations and from day to day. *Smoke Dispersion Prediction Systems* (Ferguson, 2001) generated detailed maps and statistics of mixing heights in the United States that can be useful to the analyst.

The actual magnitude of the mixing heights can be obtained from Rawinsonde balloon soundings or from remote sensing techniques, such as sound detection and ranging and light detection and ranging. These remote sensing systems are becoming more commonly used at DOE sites and provide real-time data on the vertical structure of the atmosphere; whereas Rawinsonde data is discrete and specific to the time of each balloon release; usually at 12-hour intervals. In the absence of such data, regional tables can be consulted, such as those in *Mixing Heights, Wind Speeds, and Potential for Urban Air Pollution Throughout the Contiguous United States*, (Holzworth, 1972). Each DOE site needs to technically justify their selection of mixing layer height.

E.1.5 RULES OF THUMB

For whatever model is used, some rules-of-thumb can be established for non-lofted plumes, and these may be useful for "sanity checks" of results. Such rules-of-thumb at most sites would likely be similar to the following:

- 95th percentile χ/Q value is about ten times larger than the median χ/Q value for any distance;
- 50th percentile (median) χ/Q values for ground-level releases are similar to those of Class D and 4.5 m/s wind speed;
- 95th percentile χ/Q values for ground-level releases are similar to those of Class F and 1.0 to 1.5 m/s wind speed; and,
- 95th percentile χ/Q values at ground level for elevated releases are similar to those of Class A and 4.5 m/s wind speed[55].

For lofted plumes, no such rules-of-thumb are possible as ratios of 95th percentile χ/Q to median, or some constant meteorological condition, χ/Q values vary with distance and the amount of lofting.

High-wind speed scenarios [such as sustained wind speeds of 45 m/s (100 mph)] are also of interest to the analyst. This is about 10 times greater than the wind speed that corresponds to the median χ/Q. High winds are always associated with Stability Class D, which is also the stability class associated with the median weather conditions and represents a well-mixed atmosphere. Because the value of χ/Q varies inversely as the wind speed (see Eq. E-1), the high-wind χ/Q will therefore be about 10% of the median χ/Q. As a rule-of-thumb, then, the analyst can divide the consequences (such as dose) from exposure to

[55] For elevated releases, the worst case stability class is A.

radiological or other hazardous materials for median weather conditions by 10 to find the corresponding consequences for high-wind scenarios.

Tornados have even greater wind speeds, exceeding 100 mph, and can cause a facility to collapse. This could be followed by a lower wind speed that would result is larger dispersion coefficients than the tornado itself. Section E4, *Dispersion Under a High-Wind or Tornado Event*, has a further discussion of high wind or tornado dispersion. In addition, scenarios for environmental restoration projects involving contaminated soil where the source term is based on EPA methods incorporating an assumed wind speed should be modeled with the same wind speed in the dispersion analysis (a sensitivity analysis of wind speed vs dose consequence may be necessary to determine a conservative analysis for selection of safety controls).

E.1.6 SPECIAL GAUSSIAN MODELING CONSIDERATIONS[56]

E.1.6.1 AVERAGING-TIME AND LARGE EDDY PLUME MEANDER

The above diffusion magnitude expressions in the previous subsections are relevant for short-duration plumes released over relatively smooth terrain. However, plumes tend to meander for two specific reasons: (1) when release duration is longer than some tens of minutes; and, (2) under stable light wind conditions when embedded larger eddies can dominate a relative calmly atmosphere. Large eddies, which are present in a stable, stratified atmosphere, tend to become more dominant in this situation and can augment the magnitude of lateral movement. Therefore, for a receptor that remains in the plume for some time, meandering effectively widens the plume and thus decreases χ/Q for a constant source term. This is accounted for in the Gaussian equation by multiplying the plume width (σ_y) by a plume meander factor.

Two treatments of meander are available as an option in one or more of the toolbox codes, and both involve adjustments to increase the magnitude of σ_y. One approach to plume meander is based on the influence of averaging time and is available as an option in the two radiological consequence toolbox codes, MACCS2 and HotSpot, and one toxic chemical consequence code; EPIcode. Figure E- qualitatively shows how the plume boundaries of the time-averaged plume may differ from those associated from a typical snapshot of the instantaneous plume. The second approach is related to the embedded large-eddy effects that occur under very stable atmospheric conditions.

[56] Dense gas models are applicable to chemical releases and these types of models are described in Chapter 7.

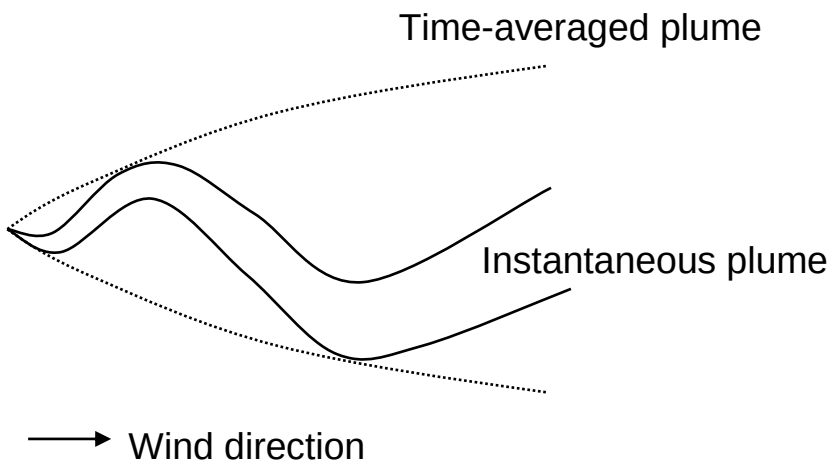


Figure E-5. Time-Averaging Effect on Plume Boundaries.

The averaging time, also referred to as sampling time, over which the σ_y values were determined from experimental data establishes the time base, usually on the order of minutes, for the horizontal and vertical diffusion coefficients. A longer averaging time than the time base may be applied in the analysis of receptor exposure times for plumes with longer release durations; this is an option the HotSpot code offers. Typically, the exposure time is assumed to equal the release duration in these analyses. A longer averaging time leads to greater apparent widening of the plume boundaries. Embedded large eddies also causes movement of the plume centerline with time (the plume swings back and forth), another type of plume meander. The receptor on the time-averaged centerline location is only exposed intermittently to the concentration of the instantaneous plume centerline due to this movement. As a result the time-averaged centerline concentration is lower. These effects become more pronounced with increasing averaging time.

The formulation for the plume meander factor[57] that is applied to σ_y based on the averaging-time concept is given by:

$$\textit{Averaging-time plume meander factor} = (\textit{plume duration / time base})^n \qquad \textbf{Equation E-8}$$

The time base for the P-G dispersion coefficients is three minutes (Pasquill, 1976; Napier et. al., 2011). The time base for the Briggs open country dispersion coefficients is typically assumed to be three or ten minutes (DOE, 2004a and DOE, 2004b; Thoman, 2006). The time base and exponent, *n*, are hard wired in EPIcode and HotSpot to values of 10 minutes and 0.2, respectively. MACCS2 allows the user to specify the time base and to input two different values of *n* to correspond to two different time ranges. Typically, the exponent is 0.2 for plume duration of one hour or less and 0.25 for longer duration (DOE, 2004c). The averaging-time plume meander factor is never allowed to be less than unity, and the experimental basis is limited to periods of no longer than 100 hours.

The other type of plume meander is related to embedded large-eddy effects that occur especially under very stable conditions with very light wind speeds and that were observed from tracer studies first performed in the mid-1970s. After careful review of the results of the tracer study, the NRC developed this plume meander factor and incorporated it in Regulatory Guide 1.145 (NRC, 1982) for atmospheric

[57] The plume meander factor is sometimes referred to as the plume expansion factor.

stability classes D, E, F, and G. It is also implemented in several of their atmospheric dispersion models such as ARCON96, RASCAL, and Version 2.6 of MACCS2 (Napier et. al., 2011). ARCON96 (NUREG-6631 Revision 1) and RASCAL increase both the horizontal and vertical diffusion magnitudes.

The large-eddy plume meander factor is applied to augment σ_y and σ_z, but only for distances up to 800 m, where its effects are damped out. Beyond 800 m, σ_y values reflect the augmented spreading up to 800 m plus non-augmented spreading beyond 800 m. The large-eddy plume meander factor ranges between 1 and 6. Its value actually increases for more stable conditions (from E to G stability class) and increases as wind speeds approach calm under the same stability class.[58] This dependency is exactly opposite to the aerodynamic building wake factor that is very small under these light wind very stable meteorological conditions, but increases significantly as the wind speeds increase and the stability class becomes neutral or slightly unstable. The faster the winds are that encounter the building, the stronger the flow separation becomes which yields a larger aerodynamic effect on the wind field.

Some atmospheric models base the meander factor on stability class instead of plume duration, as plume meander is more pronounced for low winds speeds and neutral (class D) and stable conditions (from E to G stability class). This is because large eddies are present in a stable, stratified atmosphere, which tends to augment the magnitude of the lateral movement. The Nuclear Regulatory Commission (NRC) incorporated this meander factor into Regulatory Guide 1.145 (NRC, 1982), and acknowledged it in several of their atmospheric dispersion models. This Regulatory Guide also recommends not using any meander factor for stability classes A, B, or C at any wind speeds.

E.1.6.2 MECHANICAL TURBULENCE DUE TO SURFACE ROUGHNESS

As in the case of the effect of a building on the wind field, mechanical turbulence is generated as wind flows over and around irregular obstacles on the earth's surface. Such obstacles are both natural (topographic and vegetation) and anthropogenic (buildings and other structures). In general, the rougher the terrain underneath the atmosphere moving above it, the more mechanical turbulence is generated and consequently the better the diffusion. The rougher the surface, the larger the turbulent eddies formed, mainly in the vertical, and thus the greater vertical dispersion, as expressed by an enhancement of σ_z. The increase in σ_z is called the roughness factor and it cannot be less than unity. Because σ_z is increased, the plume-centerline χ/Q is proportionally reduced by the magnitude of the roughness factor.

Mechanical turbulence continually persists once it is generated. The atmospheric mechanical turbulence at a given location reflects the upwind development of the boundary layer and the contributing influence of upwind surface elements that can be several hundred meters or more away. The surface roughness length (z_0), discussed earlier, is a measure of the amount of mechanical mixing introduced by the surface roughness elements over a region. As an approximation, the roughness length is approximately one-tenth of the actual physical height of the surface roughness elements (Hanna and Britter, 2002). In determining z_0 for application to plume transport modeling, surface characterization should thus include both upwind, also known as fetch, and downwind regions with respect to the postulated release location.[59]

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[58] Meander values of one (no widening) are associated with wind speeds of 6 m/s or larger and atmospheric stability classes A, B, and C.

[59] For example, both the release location and receptor (such as the co-located worker at 100 m) may be in the same open area that may be characterized by a small value for z_o. If this area is relatively small (a few hundred meters in diameter) and is surrounded by a building complex or forest, it may be appropriate to factor the surface elements in the surrounding region in the determination of z_o.

McElroy and Pooler first developed "urban" dispersion coefficients in *St. Louis Dispersion Study* (1968). As a rough rule of thumb, vertical dispersion is increased by one stability class for urban areas due to the additional mechanical turbulence generated by the buildings (for example, an atmospheric condition resulting in F stability in rural environments becomes E stability in urban environments). The concrete buildings also reradiate their heat at night resulting in local temperature increases, termed the urban heat island, and cause additional turbulence.

The field conditions of the Project Prairie Grass upon which the P-G dispersion coefficients were developed are characterized by a surface roughness length of 3 cm (Napier et. al., 2011). To more accurately predict dispersion for specific conditions that differ from those represented by the P-G and Briggs open country horizontal and vertical diffusion parameterizations, adjustment factors have been developed for σ_z to reflect the enhanced mechanical turbulence caused by surface roughness.[60] One commonly used formulation that has been recommended by the American Meteorological Society (AMS) is given below (Hanna, 1977).

$$\textit{Surface Roughness Factor} = (z_0/z_{ref})^{\,n} \quad (z_0 \geq z_{ref}) \qquad \textbf{Equation E-9}$$

where z_{ref} is the reference roughness length associated with the field experiments on which the χ_z curves are based. For a P-G σ_z, the reference surface roughness length is 3 cm[61]. This formulation under-predicts σ_z enhancements observed near rugged terrain (Hanna, 1977).

The exponent, *n*, of Eq. E-9 varies between 0.1 and 0.25, with larger values associated with shorter distances and rougher surfaces (Hanna, 1977; Irwin, 1980). Comparing diffusion data for surface roughness lengths of 3 cm and 100 cm for distances up to a few kilometers, in *Atmospheric Dispersion Parameters in Gaussian Plume Modeling. Part II. Possible Requirements for Change in the Turner Workbook Values*, Pasquill (1976) noted a roughness factor of approximately 2, which translates to an exponent value of 0.2. In providing guidance to SRS on dispersion analysis, the PNNL-led review team provided the recommendation that is reflected in Table E-5 (Napier et. al., 2011). Specifically, a value of 0.2 is recommended for the exponent for distances up to 5 km, and a value of 0.1 for longer distances.

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[60] Note that a surface roughness correction would not be applied with the use of the Briggs urban dispersion coefficients because these coefficients already reflect the surface roughness effect of large buildings in addition to the urban heat island influence at night.

[61] The reference roughness length for the Briggs open country set of dispersion coefficients is complicated with the empirical basis that includes data other than that from Project Prairie Grass. Napier (2011) concluded, however, that the P-G value of 3 cm is also applicable to the Briggs open country set of dispersion coefficients given that χ/Q results using the Briggs dispersion coefficients are essentially indistinguishable to those using P-G dispersion coefficients at distances less than 10 km. Based on this reasoning, the 3-cm value for z_{ref} for applications for distances greater than 10 km would reflect a conservative perspective given that the χ/Q results based on the Briggs dispersion coefficients are lower than those from the P-G dispersion coefficients.

Table E-5. Surface Roughness Adjustments Recommended PNNL-led Review Team.

Downwind Distance x (km)	0.1 < x ≤ 5.0	x > 5.0
Roughness Factor Exponent	0.2	0.1
Roughness Factor (for z_o = 3 cm)	1.00	1.00
Roughness Factor (for z_o = 30 cm)	1.58	1.26
Roughness Factor (for z_o = 100 cm)	2.02	1.42

Other approaches such as *A Scheme for Estimating the Vertical Dispersion of a Plume from Source Near Ground Level* (Smith, 1973) or Hosker (1974) adjust σ_z for surface roughness effects, such as the formulation below that relates the roughness factor to both downwind distance and z_0.

$$\textit{Surface Roughness Factor} = \ln\{c_1 \cdot x^{d1} \cdot [1 + c_2 \cdot x^{d2}] - 1\} \quad (\text{for } z_0 \leq 10 \text{ cm}) \qquad \textbf{Equation E-10}$$

$$\textit{Surface Roughness Factor} = \ln\{c_1 \cdot x^{d1} \cdot [1 + (c_2 \cdot x^{d2}) - 1]\} \quad (\text{for } z_0 > 10 \text{ cm}) \qquad \textbf{Equation E-11}$$

The downwind distance, *x*, is in km and the constants are dependent on z_0 as shown in Table E-6.

Table E-6. Surface Roughness Factor Coefficients and Exponents.

Roughness Length z_0 (cm)	c_1	d_1	c_2	d_2
1	1.56	0.0480	6.25E-4	0.45
4	2.02	0.0269	7.76E-4	0.37
10	2.71828	0	0	0
40	5.16	-0.098	18.6	-0.225
100	7.37	-0.0957	4.29E3	-0.60
400	11.7	-0.128	4.59E4	-0.78

The PNNL-led review team endorses the approach defined by Eq. E-10 and Eq. E11 citing functional consistency with the EPA approach to surface roughness adjustments in determining P-G stability class from standard deviations in the horizontal (σ_θ) or vertical (σ_φ) wind direction (Napier et. al., 2011).[62]

[62] The PNNL review team noted that a value of 15 cm is used by the EPA for z_{ref} in its guidance document for meteorological data processing (EPA 2000). This 15-cm value differs from the 3-cm value associated with the P-G dispersion coefficients. The review team reconciles this difference by noting that the EPA adjustments to the σ_θ or σ_φ ranges were developed for a site with a 15-cm surface roughness (Irwin,1980). The P-G dispersion coefficients, in contrast, were developed from experiments at the Project Prairie Grass site with a 3-cm surface

Various methods exist to estimate the surface roughness length. It may be appropriate to assign different values of z_0 for different regions of a site or for different receptor distances (such as the 100 m CW or site boundary distance) for the same postulated release from a given location. It was noted above that the wind speed profile near the earth surface is influenced by roughness effects. This allows z_0 to also be estimated from wind profile observations, if available (Hanna and Britter, 2002).

One commonly-used method for estimating the surface roughness length is based on matching site observations with guidance tables, shown in Table E-7.

Table E-7. Roughness Lengths for Various Terrain Types.

Terrain Description*	z_0 (m)
Open sea, fetch at least 5 km	0.0002
Mud flats, snow; no vegetation, no obstacles	0.005
Open flat terrain; grass, few isolated obstacles	0.03
Low crops; occasional large obstacles, x/H > 20	0.10
High crops; scattered obstacles, 15 < x/H < 20	0.25
Parkland, bushes; numerous obstacles, x/H ≈ 10	0.5
Regular large obstacle coverage (suburb, forest)	1.0
City center with high-rise and low-rise buildings	≥ 2.0

*Note: x/H is ratio of downwind distance to obstacle height

The term fetch in Table E-7 represents the roughness associated with the direction from which the wind is blowing (upwind), as the characteristics of the land covered by the wind in its path to the receptor will determine the ground roughness effects embedded in the air parcel.

An alternative approach is to use the EPA AERSURFACE software, which is based on input of 1992 National Land Cover Data (NLCD92) from the USGS (EPA, 2008). The USGS NLCD92 data (http://landcover.usgs.gov/natllandcover.php) utilized by AERSURFACE consists of land cover data at spatial resolution of 30 meters, mapped using an Albers Conic Equal Area projection, and based on a 21-category morphology classification scheme. AERSURFACE can be used to determine variations by sector, distance, and season, or an overall composite value.

MACCS2 allows the roughness factor to be entered as a user input that is used to scale σ_z. Historically, Eq. E-9 has been used given its presence in MACCS2 software documentation (DOE, 2004c; Jow, 1990). None of the other DOE Central Registry codes allow for surface roughness adjustments to σ_z. The meteorological data file for GENII2, however, does include an input value for z_0, but it is not used to

roughness.

calculate a roughness factor. It should be noted that the z_0 value is a key input for the deposition velocity calculation of GENII2.

SRNL recently performed a study, *Roughness Lengths for the Savannah River Site* (Weber et. al., 2012), where surface roughness was computed from H-Area tower 2010 15-minute-averaged meteorological data measured at 61 m above the tree canopy using mechanical bivanes. Using the standard deviation of elevation angle and applying a simple formula based on tree canopy height, consistent estimates for roughness around the H-Area tower resulted in a mean value of surface roughness of 1.81 m. Application of this method for the 61-m level at D-Area and N-Area gave mean values of 1.71 m and 1.81 m, respectively. Since roughness results are azimuth dependent, as the fetch is different for each wind direction sector, the results were presented as averages over compass sectors spanning 22.5 degrees azimuth. These calculated values were compared to other methodologies that determine roughness. Additional data was obtained from a sonic anemometer at 61-m on the H-Area tower during a period of a few weeks in 2010 that supported the roughness calculations.

Based on the H-Area tower results, SRNL applies a surface roughness of 1.8 m in dispersion modeling applications. This technique can be applied at all DOE sites to determine its surface roughness. This result is consistent with the terrain type roughness length combination in Table E-7.

E.1.6.3 AERODYNAMIC EFFECTS OF BUILDINGS

The calculation of plume concentrations within the cavity and wake regions of even a simple block-like building is a very complex undertaking and generally requires Computerized Fluid Dynamics (CFD) models to account for the all of the eddies generated by mechanical turbulence. A discussion of fluid dynamic principles required to solve this problem is beyond the scope of this Handbook.

Ground-level concentrations at some distance beyond the building, such as beyond five building heights, can be approximated. Another method available is to assign a virtual point source upwind of the building such that when this virtual plume reaches the building, the concentrations at the edges of the building are 10 percent of the centerline concentration.

As discussed earlier, building wake effects are most pronounced under windy conditions, whereas the plume meander effects are most pronounced under light wind conditions.

The Pasquill-Gifford and Briggs open country dispersion coefficients represent short-duration plumes released over relatively smooth and open terrain. When the terrain is marked by natural or anthropogenic obstacles, mechanical turbulence is generated as wind flows over and interacts with these obstacles. Surface roughness length was introduced earlier and formulations were summarized to adjust χ_z for the increased vertical dispersion from this source of mechanical turbulence. These formulations attempt to codify the collective influence of the full spectrum of surface elements that are predominantly along the line of plume transport[63]. As such, the surface roughness length concept is more applicable to long -range dispersion. In the vicinity of the radiological and toxic chemical releases, dispersion is more likely to be dominated by the interaction of the plume with the wake and cavity regions of single building or a localized cluster of buildings. Releases from vents and small stacks can be entrained behind a building into its cavity due to the aerodynamic effect of the building on the wind field in which the release occurs.

[63] The contributing influence of surface elements that are several hundred meters upwind of the release may be important for receptors that are a short distance away.

The building wake dispersion models that are presented in this section typically make use of the standard dispersion coefficients, σ_y and σ_z, plus application of additional factors to capture increased dispersion from the wake effects. In implementing these models, the analysts should generally make use of σ_y and σ_z values that are free from any other adjustments such as for plume meander or surface roughness effects.[64] The building wake dispersion models presented in this section are applicable to releases that are modeled as ground-level and non-buoyant and are based on the treatment of the atmosphere as an incompressible fluid, for mathematical simplicity.

Figure E-6 depicts the cavity and wake zones[65] behind a building (Hosker, 1981). The aerodynamic effect of the building exerts two influences on the release. The first influence is the entrainment of flow in the vicinity of the building into the cavity region behind the building. The second influence is the enhancement of lateral and vertical dispersion associated with the cavity and wake regions.

The calculation of plume concentrations within the cavity and wake regions of even a simple block-like building is very complex and beyond the capability of most models, perhaps with the exception of CFDs. However, the ground-level concentrations at some distance beyond the building, such as beyond five building heights, can be approximated. Several methods have been proposed. In one, Eq. E-3 is modified to account for the cross-sectional building area, A:

$$\frac{\chi(x, y=0, z=0, h=0)}{Q} = \frac{1}{\pi(u\sigma_y\sigma_z + cA)} \qquad \textbf{Equation E-12}$$

where c is the building shape factor, usually taken to be 0.5 and A is the smallest cross-sectional area of the building between the source and receptor. Another method is to assign a virtual point source upwind of the building such that when this virtual plume reaches the building, the concentrations at the edges of the building are 10% of the centerline concentration. This corresponds to σ_y = width/4.3 and σ_z = height/2.15, a commonly applied option used with MACCS2. The distance to this virtual point source can then be back-calculated, using the existing wind speed and atmospheric stability class.

Both HotSpot and EPIcode codes allow for the specification of a vertical area source that can represent the initial dispersion (σ_{y0}, σ_{z0}) associated with cavity releases. The user inputs a horizontal dimension (L_H) and vertical dimension (L_V) to define the area source. From these input values, values of σ_{y0} and σ_{z0} are calculated, a virtual source location, upwind of the actual source is determined, and adjusted dispersion coefficients calculated as discussed above for MACCS2.

The GENII2 software has two model options for building wake dispersion, namely, the PNNL model (Ramsdell, 1995; 1998a; 1998b) and the EPA model[66] (1995) that are documented in the software design documents (Napier et. al., 2009).

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64 The use of σ_z values that are adjusted for surface roughness for example, could involve the double-counting, to some extent, of the building's impact on diffusion. The analyst will need to technically justify any use of σ_y and σ_z values that already incorporate other adjustments in its protocol.

65 The term wake is occasionally used in the published literature in reference to the cavity and wake zones, collectively.

66 GENII2 incorporates two EPA wake dispersion models, but only the one that is applicable for ground-level non-buoyant releases is discussed in this Handbook.

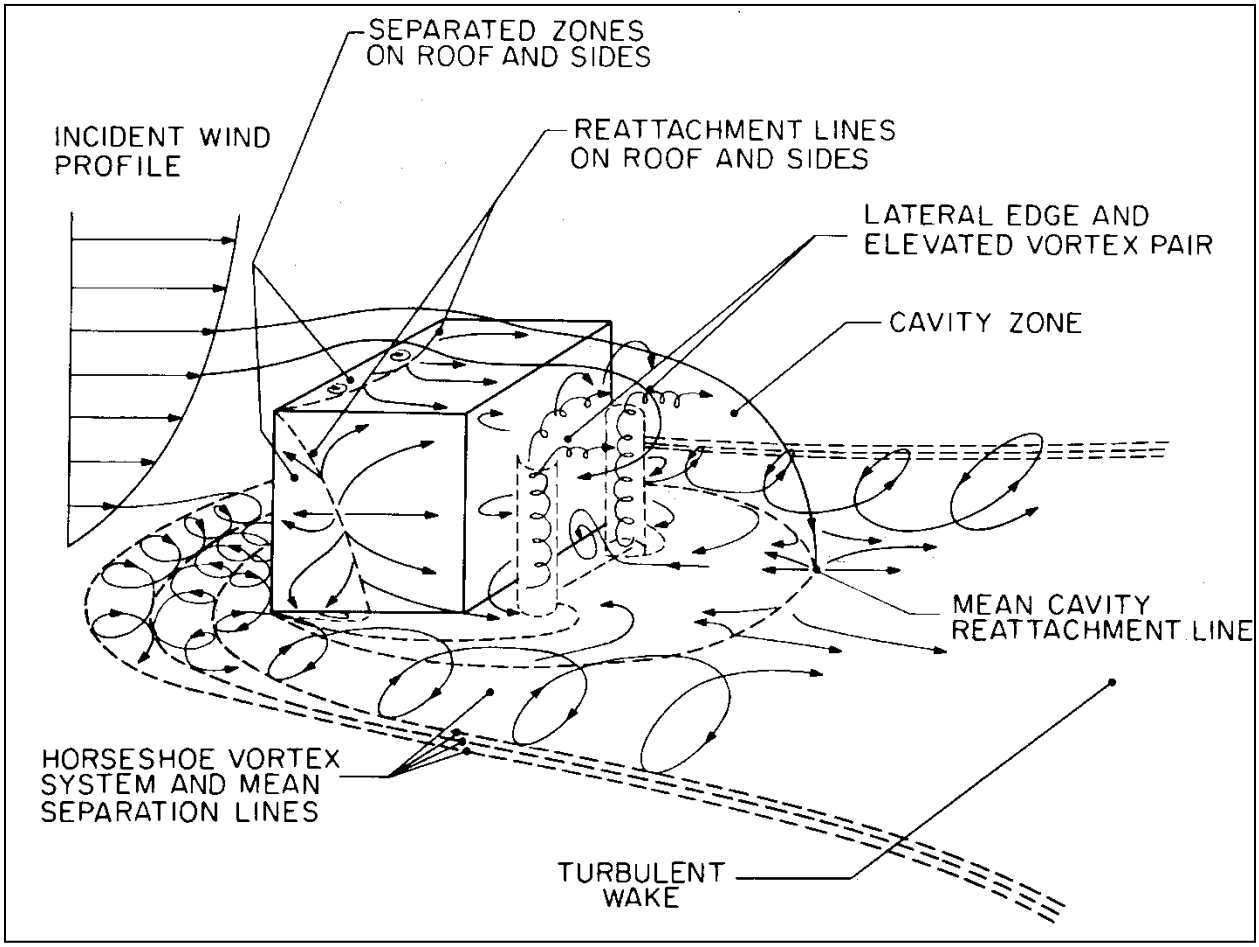

Figure E-6. Schematic of Turbulent Air Flow around a Sharp-Edged Building.

E.1.6.4 PLUME DEPLETION THROUGH DECAY, DAUGHTER IN-GROWTH, AND DEPOSITION PROCESSES

Atmospheric dilution and diffusion dominate the redistribution processes but they are not the only processes that affect the concentration distribution of a radioactive or toxic chemical material in a plume. With respect to radioactive materials, the concentration of a radioisotope of interest can decrease with time through a radioactive decay process, or can increase through the decay and in-growth of another isotope. Mass transfer processes in the atmosphere remove gases and particulates from the plume and can also reinsert particulates back into the atmosphere. The primary removal processes are dry deposition from gravitational settling and fallout, and wet deposition or precipitation scavenging from rain, snow, or hail. Reinsertion of deposited material back into the atmosphere to be transported to a new location is termed resuspension and is also discussed below. These mass transfer processes are important in determining the ultimate fate of small, respirable particulates, as well as ingestible particulates from radioactive compounds and chemically toxic materials.

The parameter *Q* represents the rate of release of material into the atmosphere. In the following discussion, the meaning of this parameter is extended to include other processes that change the radionuclide abundances and quantities of the material. These include decay and in-growth, removal of the material by dry and wet deposition processes, and resuspension of removed material. It may be noted

that in some atmospheric dispersion models, the quantity χ/Q refers to only the atmospheric dispersion processes discussed earlier. Other models include the other processes discussed below. In RG 1.111, NRC introduces the term depletedχ/Q, which is the concentration in the plume after dry deposition processes have removed, or depleted, some the material. NRC RG 1.111 also introduces the term D/Q, which is dry deposition. Accordingly, when using atmospheric dispersion models, it is important to note which definition is being used for χ/Q.

In-growth and decay of radioactive materials immediately occurs following their release into the atmosphere, regardless of the location of the material, whether within the plume, in materials that have fallen to the ground, or in materials that have been resuspended into the air. Decay refers to the loss of a given isotope through radioactive disintegration over time. In-growth refers to the build-up of one isotope by the decay of another, that is, it is the daughter product of the decay of this other isotope, termed the parent. The abundance of an isotope at any given time is a function of its decay rate as well as that of the parent isotope, if any, and the time since release.

For the initial atmospheric plume, not the resuspended plume, the time t is simply the transport time, that is, the distance (x) traveled divided by the average transport wind speed (u). For material deposited on the ground or for a resuspended plume, the time t will, of course be longer. The concentration of isotope i can be adjusted by multiplying the χ/Q by $A_i(t)/A_i(0)$ to account for the decay and in-growth of isotope i.[67] This is not of concern for long-lived, slowly decaying isotopes, such as Pu-239, but can be important for shorter-lived fission products from a criticality.

The rate of dry deposition is usually expressed in terms of a deposition "velocity" (V_d), a term having the units of velocity that expresses the rate of mass-transfer from the plume to the ground at the atmosphere / ground-surface interface. The deposition "velocity" is defined as a deposition flux, ω_d (Bq m^{-2} s^{-1}) divided by the near surface air concentration, χ (Bq m^{-3}):

$$V_d = \omega_d(x, y) / \chi x, y, 0\chi \qquad \textbf{Equation E-13}$$

The dry deposition velocity is essentially a proportionality factor, and although it has the same units as a velocity, it is not a true velocity. A variety of mechanisms contribute to dry deposition. Gravitational settling is the dominant contributor for particles with diameters greater than 10 microns Activity Median Aerodynamic Diameter (AMAD)[68]. For smaller-sized particles in the respirable range (<10 microns) other processes dominate, including turbulent diffusion, surface impaction, and Brownian diffusion. Values of V_d are a function of numerous meteorological variables (wind speed, atmospheric stability), impingement environment (such as terrain, land-use type, vegetation), and the particle size distribution and density of the particles. Generally, values for dry deposition velocity increase with increased wind speeds, atmospheres that are more unstable, larger particle sizes, and terrain with higher surface roughness values. From various field experiments conducted over many years, dry deposition velocities are found to vary widely by several orders of magnitude, from 0.001 cm/s to 180 cm/s for particulates and from 0.002 cm/s to 26 cm/s for gases. Regardless of how V_d is determined, there are large uncertainties associated with it and there is currently no single accepted theoretical description of dry deposition that covers all common natural environments. However, reasonable parameterizations exist for many conditions of interest and are reasonably accurate for the conditions from which they were developed.

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[67] See Appendix G for further discussion,

[68] Activity Median Aerodynamic Diameter is the diameter of the particle for which half the activity is associated with particles larger than and half the activity associated with particles smaller than this size particle.

Early dry deposition models included *A Model for Predicting Dry Deposition of Particles and Gases to Environmental Surfaces* (Sehmel and Hodgson, 1978) model; developed from wind tunnel experiments. The results of this model are consistent with a wide-range of historical deposition velocity measurements but do not take into account the effects of atmospheric stability or surface roughness from different land-use categories that were outside the scope of the aforementioned wind tunnel studies. The default deposition velocity values originally recommended in the DOE Guidance Report for MACCS2 (DOE, 2004) were based on the Sehmel and Hodgson model.

The current generation of atmospheric diffusion and transport models estimate the deposition velocity by analogy to electrical systems, where the deposition velocity is formulated as the inverse of the sum of resistances. GENII and other models incorporate resistance-based deposition models. In these models the deposition velocity is calculated in time and 3-dimensional space because its value is dependent on time-varying atmospheric conditions and 3-dimensional variable surface characteristics.

An Extended Dry Deposition Model for Aerosols Onto Broadleaf Canopies (Petroff and Zhang, 2010) represents the latest research in dry deposition modeling and is constructed under the premise that while no single theoretical description of deposition processes exists that is valid for all land use types, deposition properties should be possible to parameterize over a wide range of natural environments based on available deposition velocity measurements. This model provides one of the most complete theoretical descriptions of deposition available and has been parameterized to match a large number of experimental data sets covering multiple surface types and land-use characteristics. This model has not yet been incorporated into any widely-used atmospheric dispersion models but is being tested for implementation into the National Atmospheric Release Advisory Center (NARAC) Lagrangian Operational Dispersion Integrator (LODI) dispersion model. The assorted models are summarized inFigure E-9.

The DOE Safety Software Central Registry includes atmospheric transport models that either internally calculate deposition velocity using a formulation of a dry deposition model or that require the user to specify an appropriate value. For models like GENII2 that include a dry deposition model within the code, appropriate site-specific parameters (particle size, particle density) should be specified that are representative of site conditions. The analyst should follow the accompanying DOE guidance document, if one is available, for inputting site-specific parameters and follow the requirements in DOE-STD-3009-2014 for radiological consequences modeling.

Other atmospheric dispersion models, and DOE toolbox codes such as MACCS2 and HOTSPOT, require that deposition velocity be specified by the user. Guidance for specifying an appropriate value is typically contained within the software user's manual or within the accompanying DOE Guidance Documents (DOE, 2004a; 2004b; 2004c). For a more conservative simplistic analysis, it is recommended that a default deposition velocity value be specified. The latest guidance from DOE contained in DOE-STD-3009-2014 specifies a deposition velocity of 0.1 cm/s for unfiltered release of particles (1-10 um Aerodynamic Equivalent Diameter), 0.01 cm/s for filtered particles, or 0 cm/s for tritium and noble gases. Although using 0.1 cm/s or using 0 cm/s will produce virtually the same results, for close-in distances, a non-zero value acknowledges that particulate deposition is occurring. For DOE reservations with distant site boundaries, a 0.1 cm/s dry deposition velocity may significantly lower the dose.

When a more site-specific value is desired to refine the analysis, the analyst may calculate a site-specific value using an external dry deposition model (e.g. GENII2, CALPUFF, Petroff and Zhang), and then use the calculated value as an input parameter to the code. Site-specific values are desirable when the default value produces overly-conservative estimates of exposures. External models should be evaluated for appropriateness for the situation being modeled. External models can be used in one of two ways: 1)

executing the model after applying appropriate SQA; or, 2) performing a hand calculation or spreadsheet using the deposition velocity model formulation. Typically the specific model formulation can be obtained from the model's software design document or from the original published literature. The analyst should also follow the guidance specified in DOE-STD-3009-2014 for using site-specific methods and the dispersion modeling protocol in Chapter 6, Section 6.1.11.

Table E-8. Summary of Deposition Velocity Models of Interest (This table was reproduced from Sugiyama et. al., 2014).

Model	*Aerodynamic Resistance r_a (s/m)*	*Quasi-laminar sublayer resistance r_b (s/m)*	*Surface Transfer Resistance r_c (s/m)*	*Settling velocity v_s (m/s)*	*Deposition velocity, v_d (m/s)*
Sehmel and Hodgson (1978)	$A = f(Sc, D_p, u_*, z_o, D_b)$			$\frac{(\rho_p - \rho_g) g D_p^2 C}{18\mu}$	$\frac{v_s}{1 - e^{-v_s / u_* e^A}}$
GENII/ RATCHET	$u(z_d) / u_*^2$	$6.5 / u_*$	100	$\frac{(\rho_p - \rho_g) g D_p^2 C}{18\mu}$	$\left(\frac{1}{r_a + r_b + r_t + r_a r_b v_s}\right) + v_s$
AERMOD/ CALPUFF	$u(z_d) / u_*^2$	$\frac{1}{u_*\left(Sc^{-2/3} + 10^{-3/St}\right)}$	-	$\frac{(\rho_p - \rho_g) g D_p^2 C}{18\mu}$	$\left(\frac{1}{r_a + r_b + r_a r_b v_s}\right) + v_s$
Petroff and Zhang (2010)	$A = f(Sc, D_p, z_o, LAI, u_*, L, D_b, d, T, h, ObstSize)$*			$\frac{\rho_p g D_p^2 C}{18\mu} + V_p$	$\left(\frac{1}{r_a + r_b}\right) + v_s$

u_*	= friction velocity (m/s)	D_p	= particle diameter (m)
v_s	= settling velocity (m/s)	Sc	= Schmidt number
z_o	= surface roughness length (m)	St	= Stokes number
d	= zero-displacement height (m)	LAI	= leaf area index (dimensionless)
h	= canopy height (m)	L	= Obukhov length scale (m)
μ	= dynamic viscosity of air	T	= ambient air temperature (K)
D_b	= Brownian diffusivity (m^2/s)	ObstSize	= characteristic obstacle size (m)

*The Petroff and Zhang model uses a complex formulation that depends upon the dominant land-use category, the Obukhov length, the surface friction velocity, the air temperature and the particle size distribution as inputs.

Per DOE-STD-3009-2014, wet deposition is not evaluated in DOE hazard and accident analyses, however, will be addressed here for completeness to include a discussion of this phenomenology. Wet deposition, or precipitation scavenging, is more difficult to parameterize than dry deposition, as it depends upon cloud physics parameters that vary in time and space that are usually unavailable to the analyst. Each type of precipitation (rain, snow, or hail), passing through the plume collects particulates by accretion and scavenges soluble gases. The rate of depletion by wet deposition, *dQ/dt*, is proportional to the amount of material in the plume. Thus,

$$dQ / dt = -\Lambda Q \qquad \textbf{Equation E-14}$$

where Λ represents the washout coefficient (s^{-1}). The solution to Eq. E-14 over a time interval Δt gives

$$Q / Q_0 = exp\ (-\Lambda\ \Delta t)$$ **Equation E-15**

As with dry deposition, Eq. E-15 would be an adjustment factor to apply to χ/Q for wet deposition occurring in the distance interval Δx during time interval Δt. Q_0 represents the amount of material entering this interval and Q represents the amount leaving. The value of Δt depends on wind speed and the distance interval being evaluated.

The washout coefficient, Λ, is a function of the precipitation rate, the type of precipitation, and type of material being scavenged (particulate or gas). For particulates in rain, the washout coefficient can be approximated by a power law of the rainfall rate:

$$\Lambda = a\ I^{\ b}$$ **Equation E-16**

where I is the precipitation rate (such as mm/hr) and a and b are dimensionless constants that depend upon the particle size distribution. For example, in the MACCS code (Chanin et. al., 1990), the values used are $a = 9.5\times10^{-5}$ and $b = 0.8$. For gases, the washout coefficient depends upon the solubility of the effluent as well as the precipitation rate. Families of empirical curves have been developed for various rainfall rates to estimate the washout coefficient. This procedure is made more complex by the spatial variability of the rainfall. Frequently, rainfall rates vary significantly within a rainfall event, and different washout coefficients may need to be applied to various segments of the plume as it travels to the receptor. This is virtually impossible to do with a steady-state Gaussian model and would need to be addressed by 3-dimensional Lagrangian mass-consistent codes. The use of a Doppler radar system to provide spatial representations of precipitation rates can assist this calculation.

An accurate estimation of washout is needed in the near field for elevated releases because of the efficiency of this removal process for both particulates and gases. As an example, during an unscheduled release from the Ginna Nuclear Plant in 1980, the *maximum* ground-surface concentrations of ^{131}I were measured just beyond the containment building in the snow. In addition, larger doses from the Fukushima release in 2011 were the result of wet deposition that occurred days after the release. Although accurate estimations of washout are needed, most computer models treat it in only a cursory manner, if at all.

Plume depletion accounts for the material removed by either or both of the deposition processes, and accordingly reduces, or depletes, the χ/Q value. Depletion by either dry or wet deposition processes also results in soil contamination. Contaminated soil can be subsequently resuspended as a new source term should the soil be dry coupled with windy atmospheric conditions. Resuspension is generally higher in urban regions due to increased anthropogenic activities.

Although resuspension processes can contribute to exposure to individuals, the acute effect is small and therefore DOE-STD-3009-2014 does not require its inclusion in a DSA analysis.

E.1.6.5 PRINCIPLES GOVERNING PLUME RISE

Two physical processes can each propel a neutrally-buoyant plume vertically upward to a level higher than that of its initial release, an effect called plume rise or plume lofting. The first process is termed momentum plume rise, in which the vertical efflux velocity of the radiologic or toxic chemical release propels the plume upward, further above its elevated emission point. The second process is termed buoyancy plume rise, which occurs if the temperature of the plume is warmer than that of the ambient air. For either mechanism, it is important to account for stack-tip downwash of the plume. Downwash can

occur under high wind-speed conditions, and it can also occur if the release is from a vent or small stack into the wake and cavity behind the building. A brief discussion follows on both of these plume rise processes and their interactions with forces that may cause downwash. A series of equations are identified below that can be integrated into an atmospheric dispersion model to account for these effects. Most atmospheric dispersion models calculate both momentum rise and buoyancy rise and consider that the dominant one is the one giving the greater plume rise.

E.1.6.5.1 MOMENTUM PLUME RISE

The calculation of momentum plume rise requires knowledge of the vertical efflux speed and the horizontal wind speed at the point of release, and the diameter of the stack from which the effluent is released[69]; the smaller the stack diameter the greater the efflux speed for a given mass flux. As the plume is transported downwind and away from its source of momentum, the upward momentum is gradually dissipated and ultimately the wind bends the plume over into the horizontal plane. The amount of momentum plume rise is a function of the ratio of the vertical efflux speed to the wind speed. Any additional plume rise only occurs due to plume buoyancy effects.

For radioactive effluents that are released from free standing stacks whose design meet the EPA Good Engineering Practice (GEP) stack height criteria, the entire effluent escapes the influence of the facility structures. GEP stack height is defined as 1.5 times the height of the nearest facility structure plus either the height or width of that structure, whichever is larger[70]. For releases from structures that meet GEP stack height criteria, and under neutral or unstable stability conditions (stability classes A – D), plume rise can be calculated from:

$$\Delta h = 1.44\, d\, (v_e / u)^{2/3}\, (x / d)^{1/3} - C \qquad \textbf{Equation E-17}$$

where Δh is the amount of plume rise (m) above the release level, v_e is the efflux speed (m/s), u is the wind speed (m/s), x is the downwind distance (m), and d is the diameter of the stack (m). This equation shows the relationship between the two competing parameters, v_e, and u. C is the downwash correction factor and is set to zero if $v_e/u \geq 1.5$, or

$$C = 3\, (1.5 - v_e / u)\, d \qquad \textbf{Equation E-18}$$

if $0 < v_e/u < 1.5$. Under stable atmospheric conditions (E – G stability classes), the following two empirical equations are evaluated, and the smaller value is applied:

$$\Delta h = 4\, (F_m / S)^{1/4} \qquad \textbf{Equation E-19}$$

and

$$\Delta h = 1.5\, S^{-1/6}\, (F_m / u)^{1/3} \qquad \textbf{Equation E-20}$$

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69 Momentum plume rise equations do not apply to stacks that direct the plume horizontally or downward ("J" stacks).

70 Note that 1.5 times height of building plus height of building equals 2.5 times height of building, which matches the NRC guidance. If the building is squat (wider than tall) "1.5 times height plus width" will exceed the "2.5 times height" rule.

where F_m is the momentum flux

$$F_m = v_e^2 (0.5\ d)^2 \qquad \textbf{Equation E-21}$$

S is the stability parameter

$$S = (g / T)\ (d\chi dz) \qquad \textbf{Equation E-22}$$

g is the acceleration of gravity (m/s^2), T is the ambient temperature (K), and $d\chi dz$ is the potential temperature lapse rate (K/m), which is the sum of the actual temperature lapse rate and adiabatic lapse rate.

For plume rise from non-GEP stacks or building vents, empirical relationships from field studies have been developed at the Millstone Nuclear Power Plant in 1978. The key result of this study is that there are two forces acting on the plume. The efflux velocity (v_e), which can be visualized as an escape velocity, and wind speed (u), which can be visualized as a capture velocity. Accordingly, the v_e/u ratio is the driving parameter. When $v_e/u > 5$, the vertically-directed momentum flux, which affects escape from the building, dominates the horizontally-directed wind speed, which affects capture in the building wake, and the release is treated as elevated. This means that although the release emanated from a short stack or a vent, it still will fully escape the aerodynamic effects of nearby buildings due to the high momentum flux coupled with low wind speed. The GEP stack height equations apply in this case. On the other end of the spectrum, when $v_e/u < 1$, the release is effectively ground-level and no plume rise occurs. Two intermediate cases were also developed from the field study. These are the partially entrained and the partially elevated cases and are expressed in terms of an entrainment coefficient, E_t, which is the fraction of the plume entrained into the wake and cavity behind the building. The remainder escapes entrainment.

<u>Partially Entrained</u>: For cases where $1.5 < v_e/u < 5$, a portion of the plume is entrained and the remainder of the plume remains elevated. An entrainment coefficient can be calculated for this case as follows:

$$E_t = 0.30 - 0.06\ v_e / u \qquad \textbf{Equation E-23}$$

<u>Partially Elevated</u>: For cases where $1 \leq v_e/u \leq 1.5$, an entrainment coefficient can be calculated for this case as follows:

$$E_t = 2.58 - 1.58\ v_e / u \qquad \textbf{Equation E-24}$$

In both of these cases, the elevated portion of the plume is subject to plume rise, while the entrained portion of the plume is down-washed to ground level.

E.1.6.5.2 BUOYANCY PLUME RISE

The calculation of buoyancy plume rise requires knowledge of the effluent temperature or the energy released in a fire and the ambient temperature at the point of release. If the plume temperature is higher, positive (upward) buoyancy occurs, while for a relatively cold plume, negative buoyancy occurs. The stability class of the atmosphere also affects the buoyancy rise, at least initially. Unlike momentum rise, which may take only 30 to 40 seconds, buoyancy rise may continue for many minutes due to its slower upward speed compared to momentum rise. The buoyancy rise can be calculated in two parts. The first is the initial rise and is dependent on the stability class. The second is the gradual rise and is independent of stability class. The larger of the two is then chosen as representative.

The initial plume rise is independent of distance downwind, but is dependent on stability class. For classes A – D, and buoyancy fluxes less than 55 m^4/s^3, the plume rise is given by (Briggs, 1975)

$$\Delta h = 21.425\, F_b^{\,3/4}\, u^{-1} \qquad \textbf{Equation E-25}$$

where F_b is the buoyancy flux. For fluxes greater than 55 m^4/s^3, the plume rise is given by

$$\Delta h = 38.71\, F^{\,3/5}\, u^{-1} \qquad \textbf{Equation E-26}$$

For classes E – G, the plume rise is given by

$$\Delta h = 2.6\, [F_b / (u\, S)]^{1/3} \qquad \textbf{Equation E-27}$$

except for calm conditions, for which it is appropriate to use

$$\Delta h = 4\, F_b^{1/4}\, S^{-3/8} \qquad \textbf{Equation E-28}$$

The gradual plume rise, which is independent of stability class, can be calculated from the empirical relation

$$\Delta h = 1.6\, F_b^{1/3}\, x^{2/3}\, u^{-1} \qquad \textbf{Equation E-29}$$

The buoyancy flux depends upon whether the release is from a stack or from a fire. For a stack release, the buoyancy flux is

$$F_b = g\, v_e\, d^2\, \Delta T / (4\, T_s) \qquad \textbf{Equation E-30}$$

Where, ΔT is the stack gas temperature (T_s) minus ambient temperature. For a fire it is given by

$$F_b = 8.79 \times 10^{-6}\, \Omega \qquad \textbf{Equation E-31}$$

where Ω is the rate of release of sensible heat (watts)[71]. Eq. E-28 would let the plume rise indefinitely, so it is necessary to cap the plume rise. Several methods of capping the buoyancy rise have been used. One way of doing this is to terminate the use of Eq. E-26 when one of the following conditions occurs: (1) when Δh reaches $300\, F_b/u^3$ (Briggs, 1975); (2) when the plume centerline has reached the height of the top of the mixed layer; or (3), when one hour has elapsed since plume release began.

E.1.6.6 PLUMES FROM ENERGETIC EVENTS[72]

In the initial phase of an energetic event in air, a volume of gas is created that is hot and of high pressure. Because the gas is hot, it rises through its own buoyancy and by the overpressure of the event (see Chapter 3). This gas expands rapidly until it equilibrates with the atmospheric pressure. These initial

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[71] The total energy released in a fire can be partitioned into various forms, such as sensible heat, radiant heat, and latent heat. Sensible heat gives rise to changes in temperature and density and thus determines the buoyancy flux.

[72] See Chapter 7 for additional discussion.

processes determine the plume's initial dimensions and height. After it reaches equilibrium with the ambient atmosphere, conventional atmospheric diffusion processes act on this plume, carrying it downwind as it continues to expand through turbulent diffusion.

HotSpot version 2.07.01 Code (Homann, 2010), includes atmospheric dispersion models for a nuclear explosion, non-nuclear plutonium explosion, non-nuclear uranium explosion, fire and tritium release. These models estimate the short-range (<10 km) downwind radiological impact following the release of radioactive material resulting from a short-term release (<few hours), explosive release or fuel fire event. The nuclear explosion program estimates the effects of a surface-burst nuclear weapon, which includes prompt effects (neutron and gamma, blast, and thermal).

Virtual source terms are used to model the initial atmospheric distribution of source material following an explosion and fire. The release is partitioned into 5 segments at varying heights up to the cloud top with upward virtual source terms as shown in Section 7 (*HotSpot Algorithms*) of the HotSpot 2.07.1 User's Manual, reproduced in Figure E-. The cloud radius is equal to 0.2 cloud top.

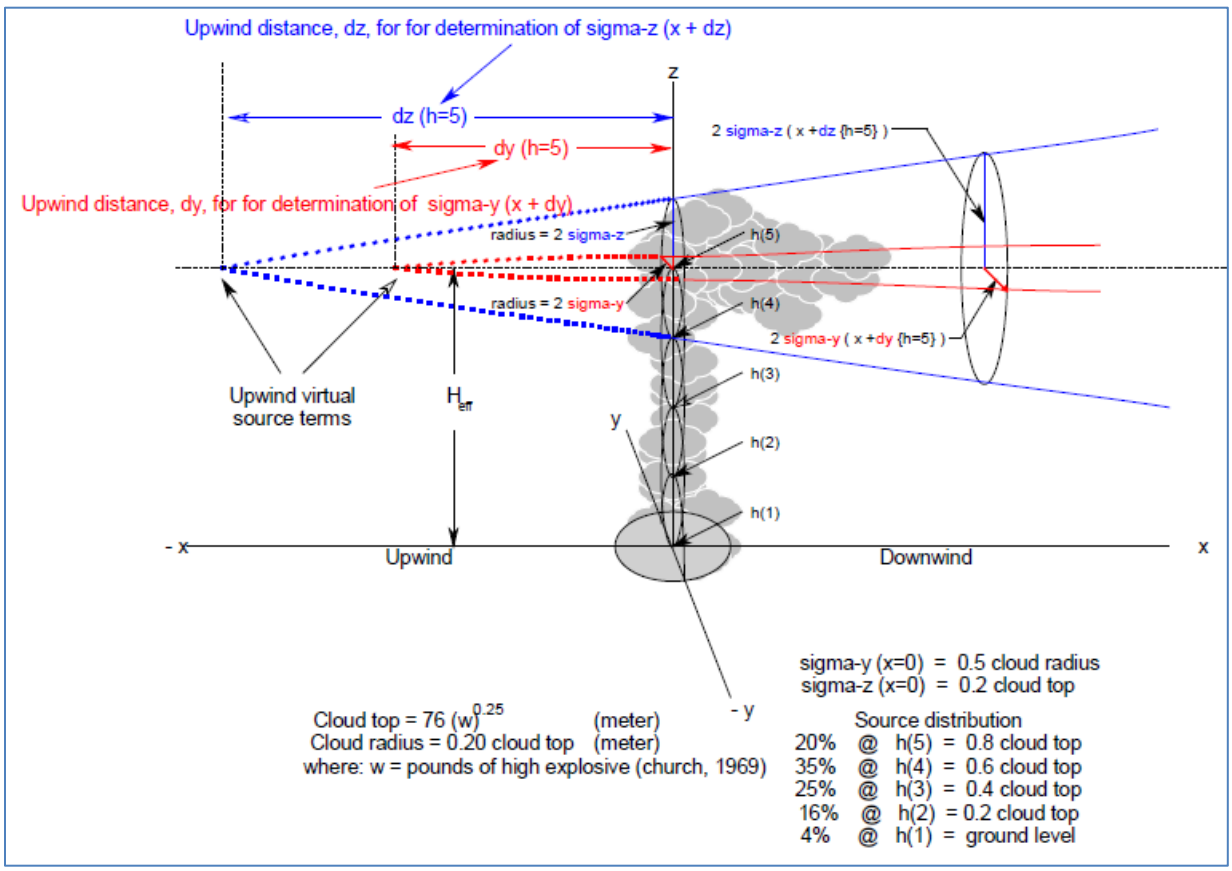

Figure E-7. Virtual Source Terms used in HOTSPOT for Explosion or Fire.

The non-respirable release component is the fraction of the total quantity of material involved, available for dispersion into the atmosphere, which has a separate non-respirable deposition velocity default value of 8 cm/sec, and is used to determine ground shine, submersion, and plume depletion.

Another code has been developed expressly for this purpose, the Explosive Release Atmospheric Dispersion (ERAD) code from Sandia National Laboratories (Boughton and DeLaurentis, 1992). This

code is a three-dimensional numerical simulation of particle dispersion in the atmosphere and includes cloud dynamics, buoyancy effects, and turbulent diffusion. It was designed to run on a small field-deployable computer. The details of this model are beyond the scope of this guidebook, but to summarize, it treats particle dispersion as a stochastic process that can be simulated with a Lagrangian Monte Carlo method. Comparisons with field tracer data (Roller Coaster) show reasonably good agreement between the model predictions and measurements.

ERAD is difficult to use, in that the required array of three-dimensional meteorological data cannot be easily obtained for code input, and the final consequence statistics cannot be easily derived. An alternative method was therefore derived that makes use of a dispersion and consequence code that is commonly used at DOE sites, namely, MACCS2 (see below). In this method, *Plutonium Explosive Dispersal Modeling Using the MACCS2 Computer Code,* (Steele, 1998), equations are derived that give the cloud top height and the cloud radius as a function of time and amount of explosive used. Because the plume asymptotically approaches the "final" height and size, the expressions are evaluated at three minutes following the detonation, as the height and size are nearly the same then as their asymptotic values. This leads to two simple expressions. The cloud top height (*CTH*) is given by

$$CTH\ (m) = 75\ w^{1/4} \qquad \textbf{Equation E-32}$$

where *w* is the weight of the explosive in pounds of TNT equivalent. The cloud radius is

$$R\ (m) = 16\ w^{1/4} \qquad \textbf{Equation E-33}$$

These expressions are found to match observations surprisingly well. For use in MACCS2, the initial height of the plume is set to $CTH - R$, and the initial cloud size is set to $\sigma_y = \sigma_z = R$. The resulting plume concentrations are found to match observations about as well as ERAD did.

E.2 CO-LOCATED WORKER DISPERSION FACTOR

As mentioned in Chapter 6, Section 6.1.2, *Key Receptors*, the CW is a hypothetical individual located at a distance of 100 meters from a facility (building perimeter) or estimated release point. Unmitigated CW dose calculations are used to evaluate whether safety significant (SS) controls are needed for protection of onsite workers. DOE-STD-3009-2014 Section 3.2.4.2 requires that:

> *"A χ/Q value of 3.5×10^{-3} sec/m^3 shall be used for ground-level release evaluation at the 100 meter receptor location unless an alternate onsite χ/Q value is justified. This value may not be appropriate for certain unique situations such as operations not conducted within a physical structure. When an alternate value is used, the DSA shall provide a technical basis supporting the need for the alternate value and the value selected."*

The threshold for designation of SS controls is a 100 rem dose and the χ/Q value of 3.5×10^{-3} s/m^3 is part of the unmitigated dose calculation for the 100-m CW receptor. New nuclear facilities or major modifications to existing facilities apply the χ/Q value specified in the Standard; however, there may be a limited number of situations where this value is not appropriate for the release conditions, and an alternate value may be more appropriate. DOE Technical Report NSRD-2015-TD01 and OE-3 were issued in 2015 to establish the regulatory basis of this χ/Q value. A discussion of this technical report and OE-3 follows.

E.2.1 TECHNICAL REPORT FOR CW X/Q VALUE

Technical Report for Calculations of Atmospheric Dispersion at Onsite Locations for Department of Energy Nuclear Facilities, NSRD-2015-TD01, assesses the "default χ/Q value" and its technical and regulatory bases. The purpose of the technical report is to explore the sensitivities of the radiological χ/Q value, previously stated in Appendix A to DOE-STD-1189-2008, *Integration of Safety into the Design Process*, identify any limitations associated with this value, and evaluate whether its use for toxic chemical release calculations, stated in Appendix B to DOE-STD-1189-2008, is conservative. The χ/Q value in Appendix A to DOE-STD-1189-2008 was based on NUREG-1140, *A Regulatory Analysis on Emergency Preparedness for Fuel Cycle and Other Radioactive Material Licensees*, that applied Gaussian plume dispersion methodology for a 95% conservative meteorological condition with a building size of 10m by 36m, and included other commonly utilized conservative assumptions (e.g., centerline concentrations).

Although the default χ/Q value was based on a number of conservative assumptions, the technical report determined that dispersion calculations were most sensitive to variations in initial plume dimensions that were driven by the aerodynamic effects of the physical structure at the point of release. The technical report analyzed sensitivity studies using the radiological consequence codes MACCS2 and ARCON96, and the toxic chemical codes ALOHA and EPICODE, to conclude that the default χ/Q value represents a conservative estimate of dispersion for calculating both radiological and toxic chemical exposure of the CW, where the release is subject to aerodynamic effects from a facility building with a nominal cross-sectional area of 10 m by 36 m. However, the technical report also acknowledged that for uncommon situations where there is a radiological or toxic chemical release from a facility smaller than that assumed in the analysis (e.g., tank farm piping), where the enhanced turbulence from the aerodynamic effects of the facility on the wind field would be smaller, the default χ/Q value may not provide as conservative an estimate of dispersion; specifically when benchmarking against Gaussian plume models such as MACCS2.

E.2.2 ALTERNATE X/Q VALUE JUSTIFICATION

DOE-STD-3009-2014 Section 3.2.4.2 allows the application of an alternate χ/Q value as long as the need for this alternate value is justified and its technical basis is documented in the DSA. Although limited, there are situations that may warrant the use of an alternate χ/Q value. As the Technical Report demonstrates, inherent to the default χ/Q value is the assumption that the release is from a nuclear facility with a building size of at least 10 m by 36 m. However, when the building size is smaller than 10 m by 36 m, or if there is no building structure at all, the default χ/Q value may no longer be as conservative and an alternate technique is justified.

Moreover, there may still be a need for using an alternate χ/Q value when the release is from a sufficiently large building. This situation may arise when updating a DSA that was based on DOE-STD-3009-94 to DOE-STD-3009-2014. DOE sites that already have existing CW values calculated in their DSA should consider the need for updating their analysis to the specified value in DOE-STD-3009-2014 and the impact that it has on control selection. If the updated analysis establishes that no change to SS designation occurs, or no new SSCs or SACs are identified, then the DSA justification documents the selected χ/Q value, and provides a rational that use of the alternate χ/Q value would not impact safety control selection.

When an alternate χ/Q value is used in situations where the default χ/Q value may not be appropriate, the DSA justification should be commensurate with the method of calculating the alternate χ/Q value. The following two subsections discuss hand-calculation and computer code methodologies for calculating a χ/Q value where the default value is shown to not be appropriate.

E.2.2.1 HAND CALCULATIONS FOR A X/Q VALUE WHERE THE DEFAULT VALUE IS NOT APPROPRIATE

Attachment E of NSRD-2015-TD01 provides a simple approach for determining a χ/Q value in situations where the default χ/Q value is shown to not be appropriate for a conservative unmitigated analysis. The approach applies the Gaussian plume equation methodology, basing the initial plume dimensions, σ_{yi} and σ_{zi}, on the actual building width and actual building height that the release emanates from, as shown in Eq. E-34.

$$\frac{\chi}{Q}(x = 100, y = 0, z = 0, H = 0) = \frac{1}{\pi * U * (\sigma_{yi} + \sigma_{y_{100}}) * (\sigma_{zi} + \sigma_{z_{100}})}$$

Equation E-34

Where:

U = Wind speed diluting the plume (m/sec);

σ_{y100} = Standard deviation of concentration in the horizontal direction from 100 m of plume travel (m);

σ_{z100} = Standard deviation of concentration in the vertical direction from 100 m of plume travel (m);

σ_{yi} = Standard deviation of concentration in the horizontal direction based on the aerodynamic effects of the building width (m); and,

σ_{zi} = Standard deviation of concentration in the vertical direction based on the aerodynamic effects of the building height (m).

The initial plume dimensions can be calculated from Eq. E-35.

$$\sigma_{yi} = W/4.3 \quad \text{and} \quad \sigma_{zi} = H/2.15$$

Equation E-35

Where:

W = shortest building width (m); and,

H = minimum building height (m).

The intent of this approach is to address the potential issue concerning releases emanating from locations that either do not have a physical structure or where the building is smaller than 10 m by 36 m. For releases from locations without any physical structure, Eq. E-34 simply reverts to the ground-level release equation (Eq. E-3) for a plume that has traveled 100 m with no horizontal and vertical plume expansion to account for the aerodynamic effects of a facility on the wind field. This simple hand calculation or Excel spreadsheet calculation can be quickly executed without employing a dispersion computer code, which is consistent with the original intent of establishing a default χ/Q value. Examples of how to use the equation are provided in Attachment E of NSRD-2015-TD01 for different structure dimensions and when no structure is nearby. Case 2 from Table E-1 of the technical report is replicated below for releases from locations without any physical structure assuming that the 95 percent meteorology is stability class F and 1 m/s wind speed.

For stability class F at a distance of 100 m, the Eimutis-Konicek[73] curve fit algorithms give the following standard deviation of concentration in the horizontal and vertical directions without a building present.

$$\sigma_y = 0.0722 \times 100^{0.9031} = 4.62 \text{ m}$$

$$\sigma_z = 0.086 \times 100^{0.74} - 0.35 = 2.25 \text{ m}$$

$$\chi/Q = 1 / [\pi \times 1 \text{ m/s} \times 4.62 \text{ m} \times 2.25 \text{ m}] = 3.1\text{x } 10^{-2} \text{ s/m}^3$$

[73] The Tadmor-Gur curve fit algorithms are not to be used for distances within 500 m.

The above χ/Q value can be adjusted by for plume meander[74] due to longer release duration per Equation E-8. The standard deviation of concentration in the horizontal direction (σ_y) is adjusted by the plume meander factor (e.g., for a two-hour plume duration and a 3-minute time base) the plume meander factor would be (120 min/3 min) $^{0.25}$ = 2.515, yielding σ_y = 11.62 m, and χ/Q = 1.2 $x\ 10^{-2}$ s/m^3.

DOE-STD-3009-2014 Section 3.2.4.2 requires that the "*DSA shall provide a technical basis supporting the need for the* alternate *value and the value selected."* The DSA justification should explain the rationale why the default χ/Q value is not representative for the particular situation, or other rationale for not adopting the default value, and document how the σ_{yi} and σ_{zi} were calculated from structure dimensions that affect the wind field and the resultant χ/Q value used. If a release is affected by a nearby larger structure, the larger structure width and height is used in the χ/Q calculation.

E.2.2.2 COMPUTER CODE MODELING FOR A X/Q VALUE WHERE THE DEFAULT VALUE IS NOT APPROPRIATE

The following guidance is provided for a conservative unmitigated analysis when site-specific modeling is performed to estimate CW consequences at 100 m. Use of any alternate dispersion methodologies or attributes discussed below needs to have a valid technical basis and should be discussed with and approved by the DOE Safety Basis Approval Authority. The process is similar to that of documenting the proposed methodology and input assumptions in a modeling protocol, described in Section 6.1.11, *Dispersion Modeling Protocol for the Offsite MOI Consequences*. If a MOI modeling protocol is being developed, it can be extended to include the CW.

Dispersion modeling inputs for unmitigated consequences for the 100 m CW is expected to generally be the same as for the offsite dispersion and consequence analysis if using the same computer code, unless unique to the CW evaluation. Dispersion attributes for the CW unmitigated analysis are as follows, and where noted, may apply to the toxic chemical dispersion analysis.

- Use a DOE Toolbox Code and input values consistent with its guidance document such as the DOE-EH-4.2.1-MACCS2-Code Guidance, *MACCS2 Computer Code Application Guidance for Documented Safety Analysis*. Other site-specific developed computer codes or industry-recognized computer codes can be considered if they have undergone appropriate validation and verification in accordance with DOE O 414.D requirements on SQA and appropriate technical justification provided.
- Worst case meteorological assumptions (i.e., overall site 95th percentile or sector-dependent 99.5th percentile) can be based on local site meteorological data per Section 6.1.10, DOE-STD-3009-2014 *Atmospheric Dispersion Options*, for radiological and toxic chemical releases.
- Surface roughness of 3 cm (i.e., rural) is assumed for radiological and toxic chemical releases, unless an alternate site-specific value can be technically justified by peer-reviewed studies per guidance in Section E.1.6.2, *Mechanical Turbulence Due to Surface Roughness*.
- Aerodynamic effects of the facility on the wind field cannot be credited unless shown to yield more conservative or bounding results.
- Dry deposition velocities are selected consistent with the default values provided in Section E.1.6.4, *Plume Depletion through Decay, Daughter In-Growth, and Deposition Processes,* unless a site-specific value can be technically justified by peer-reviewed studies.

[74] Other computer codes evaluate plume meander differently, e.g., ARCON96's plume meander is independent of release duration and represents meander caused by larger eddies that are present in the atmosphere under stable light wind conditions.

- Plume buoyancy may be included when modeling outdoor fires or for fires venting through a large breach in the facility provided that it is not credited in a non-conservative manner.
- Dispersion coefficients are applicable to site characteristics. Tadmor-Gur dispersion coefficients are not recommended for close-in distances, under 500 meters.
- Release duration and plume meander are consistent with the MOI dispersion analysis unless there is a valid reason to adopt other assumptions unique for the CW dispersion analysis.

E.3 FINITE PLUME EXTERNAL DOSE MODELING

Depending on the mix of radionuclides, it is possible that inhalation doses may not be controlling, especially if an elevated radionuclide release has a higher proportion of strong gamma-emitting isotopes (such as Co-60, Xe-133, Cs-137). In this particular circumstance, the semi-infinite plume Gaussian model may not be sufficient for establishing radiological consequences and a finite plume external dose model may need to be applied. For an elevated plume, the concentration at the ground level and concomitant inhalation dose is zero, whereas, the dose from the gamma radiation of the overhead plume can be much greater than zero.

There are several codes that are available to calculate gamma shine doses including *External Dose Conversion Factors For Photons From Radionuclides In Finite-Plume Distributions: SkyDose Computer Code* (Momeni, 1999) and *Monte Carlo N-Particle Transport Code System* (MCNP, 1998), the latter a Monte Carlo transport code. With respect to the finite-cloud sector-average model (Hamawi, 1976), the long-term gamma-ray dose in the atmosphere from a sector-averaged plume may be expressed as a product of several factors multiplied by a sum of two attenuation integrals.

Since INL has an operating reactor (Advanced Test Reactor) that can release gamma-emitting fission products, it has included a finite plume model within its radiological consequence code, *RSAC-6 Radiological Safety Analysis Computer Program* (Schrader and Wenzel, 2001). The latest version is RSAC-8. Although ORNL has a High-Flux Irradiation Reactor (HFIR), it does not employ a finite plume code in its suite of dispersion models.

E.4 DISPERSION UNDER EXTREME WIND OR TORNADO EVENT

Dispersion under extreme (high) wind or tornado event conditions warrants additional considerations with respect to consequence analysis. The analysis performed for an extreme-wind/tornado event condition; severe enough to challenge SSC integrity, should initially address the effect of the event, including its incidence and return period, causing the release. Site-specific data may be used to characterize the extreme meteorological conditions, using a Probabilistic Wind Hazard Analysis (PWHA). Guidance for developing a PWHA is identified in ANSI/ANS-2.3-2011, *Estimating Tornado, Hurricane, and Extreme Straight Line Wind Characteristics at Nuclear Facility Sites*, DOE-STD-1020-2012, *Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities,* and the NPH Handbook (draft, 201x).

Once the SSC failure is established, consequences from the unmitigated release through the breached barrier in a less-turbulent atmosphere following the event should be evaluated at locations that include the maximum exposure point and other locations of interest. The simultaneous assumption of an extreme wind or tornado accident scenario with minimal dispersion lends high confidence as to the conservatism of the final result.

Section B.3 of NRSD-2015-TD1 (2015) refers to a 1996 study by Weber and Hunter, *Estimating Dispersion from a Tornado Vortex and Mesocyclone (U)*, that provides a peer-reviewed technique to determine downwind concentrations from releases caused by extreme winds or tornado that removed a primary confinement barrier. In the specific scenario studied, the tornado damages the structure and draws the released substance into its vortex. This scenario is comparable to an accident characterized by an instantaneous release and a short exposure time. The study is illustrative of the considerations for the conditions resulting from a tornado that would first be assessed and calculated at the maximum exposure point. A second and longer-term phase would also be included to account for a secondary release, potentially without crediting the presence of a structure. The two receptors may be at different distances from the source of release.

Weber and Hunter (1996) indicated that atmospheric transport and diffusion of a release from the facility into the environment during a tornado can be modeled with a design basis accident (DBA) dilution factor (Ψ/Q), designated for a specific class tornado and applied for the distance from the facility to the receptor. The Ψ/Q parameter (units of s/m^3) represents the time-integrated ground-level centerline air concentration normalized by the mass released, and is analogous to the χ/Q value that is calculated from the Gaussian plume equation for neutrally buoyant releases. The Fujita scale (F1 to F5) is commonly used to categorize tornadoes. For most DSAs, the tornado is assumed to be either F2 or F3. Figure E-8 shows Ψ/Q values as a function of downwind distance for different mean translational speeds of an F2 tornado. The consequence analysis should select a maximum Ψ/Q for the assumed translational speed. For example, a translational speed of 7.5 m/s leads to a maximum air concentration at approximately three kilometers downwind. The product of the maximum Ψ/Q value and the release rate yields the ground level air concentration at the maximum exposure point and locations of interest.

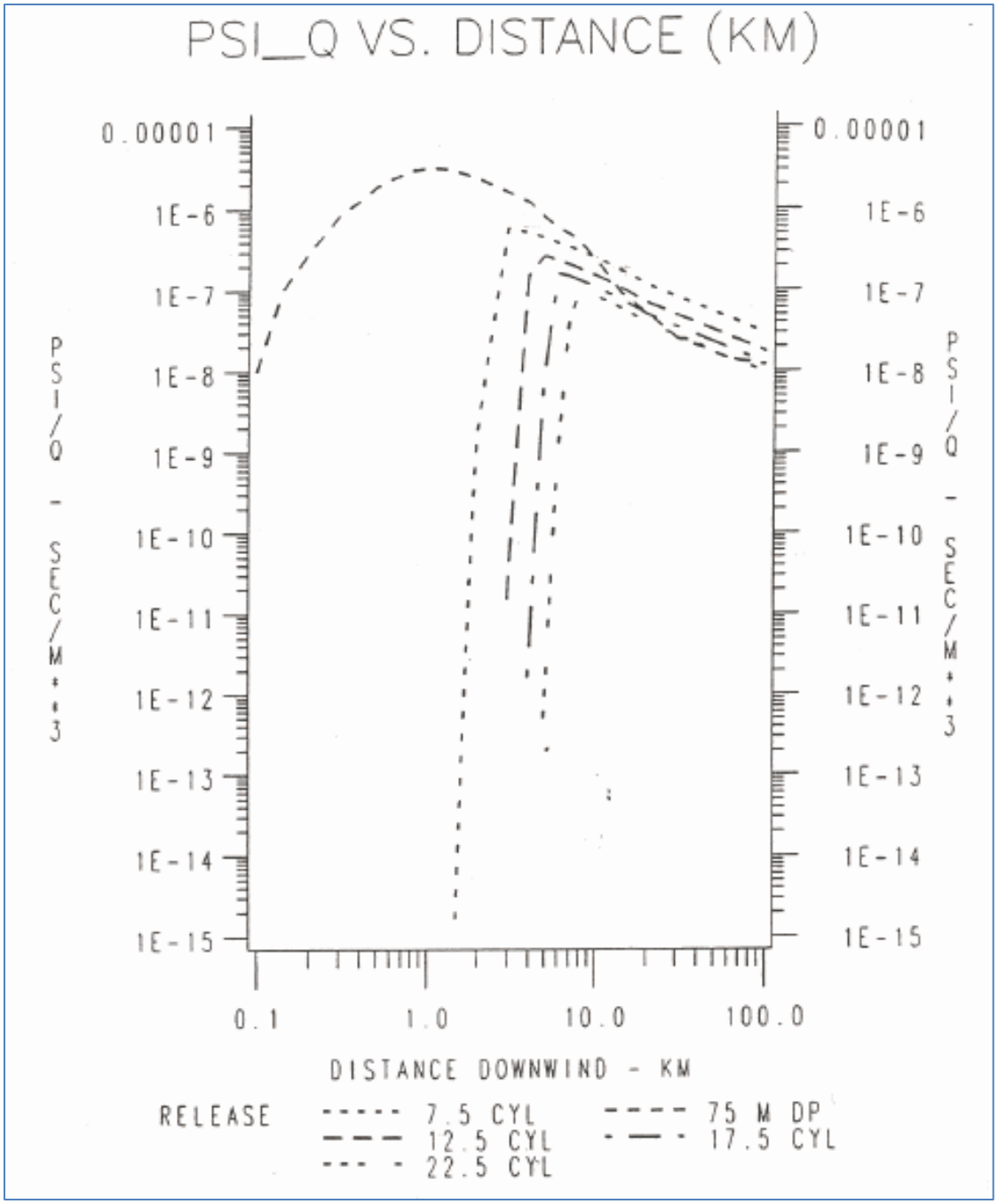

Figure E-8. Maximum time-integrated ground-level centerline air concentration (s/m^3) versus downwind distance (km) for different mean translational speeds from 7.5 m/s to 22.5 m/s. Downdraft speed is 10 m/s and height of the cylindrical mesocyclone is 3500 m (from Weber and Hunter, 1996). CYL refers to the modeled cylindrical shape of the tornado and M DP refers to the results of another tornado modeling study, for comparison.

E.5 ADDITIONAL STABILITY CLASSIFICATION TECHNIQUES

Section 6.1.6.2 presented two frequently used techniques for calculating stability class from measured meteorological parameters. The following present two additional methodologies that are not as commonly used.

E.5.1 σ_E-σ_A METHOD

This stability classification method is based on the direct measurement using three-dimensional mechanical or sonic anemometers of either the horizontal wind fluctuation (σ_A) or vertical wind fluctuation (σ_E). The initial estimates for both the σ_E and σ_A methods, based on the standard deviation of turbulence measurements are shown in Table E-10 (EPA, 2000).

Table E-9. Initial estimates of stability class based on elevation angle and azimuth angle turbulence measurements (EPA, 2000).

PG Stability Class	Standard Deviation of Wind Direction (σ_E)	Standard Deviation of Wind Direction (σ_A)
A	$11.5° \leq \sigma_E$	$22.5° \leq \sigma_A$
B	$10.0° \leq \sigma_E < 11.5°$	$17.5° \leq \sigma_A < 22.5°$
C	$7.8° \leq \sigma_E < 10.0°$	$12.5° \leq \sigma_A < 17.5°$
D	$5.0° \leq \sigma_E < 7.8°$	$7.5° \leq \sigma_A < 12.5°$
E	$2.4° \leq \sigma_E < 5.0°$	$3.8° \leq \sigma_A < 7.5°$
F	$\sigma_E < 2.4°$	$\sigma_A < 3.8°$

In addition, EPA 2000 recommends two possible additional adjustments to the σ_E-σ_A method since the turbulence typing criteria are based on measurments at the standard height (Z) of 10 m and for locations with a terrain roughness length (z_o) of 15 cm. For sites with rougher terrain and/or measurement heights different from 10-m, the category boundaries should be adjusted by wind speed measurement height and terrain roughness factors:

$$\text{Measurement Height Adjustment Factor} = (Z/10)^{p} \qquad \textbf{Equation E-35}$$

The exponent p is a function of Pasquill-Gifford (P-G) stability class and has different values for the σ_E and σ_A methods as shown in Table E-11.

Table E-10. Measurement height adjustment factor for σ_E and σ_A methods as a function of stability class.

PG Stability Class	σ_E Method p-value	σ_A Method p-value
A	0.02	-0.06
B	0.04	-0.15
C	0.01	-0.17
D	-0.14	-0.23
E	-0.31	-0.38

$$\text{Roughness Adjustment Factor} = (z_0/15)^{0.2} \qquad \textbf{Equation E-36}$$

E.5.2 SRDT Method

The SRDT method involves the use of total solar-radiation and surface wind-speed data during the day to determine atmospheric stability. During the night, ΔT_z data and surface wind-speed data are used (EPA, 2000). In this method, the wind speed is measured at or near the 10-m level or adjusted to this reference height. The SRDT method is outlined in Table E-12 (EPA, 2000).

Table E-11. Classification of Atmospheric Stability Based on SRDT Method.

	DAYTIME			
Wind Speed (m/s)	**Solar Radiation (W/m^2)**			
	≥ 925	925 - 675	675 - 175	< 175
< 2	A	A	B	D
2 - 3	A	B	C	D
3 - 5	B	B	C	D
5 - 6	C	C	D	D
≥ 6	C	D	D	D
	NIGHTTIME			
Wind Speed (m/s)	**Vertical Temperature Gradient**			
	< 0		≥ 0	
< 2.0	E		F	
2.0 - 2.5	D		E	
≥ 2.5	D		D	

APPENDIX F AQUATIC DILUTION AND GROUNDWATER TRANSPORT

F.1 OVERVIEW OF AQUATIC DILUTION AND GROUNDWATER TRANSPORT

A less frequent mode of release to be considered in the accident analysis for DOE facilities is that of hazardous species borne by aqueous or liquid discharges, outside the boundaries of facility. As described in Chapter 6, the dose pathways to be considered for calculation of the dose to the public for the the consideration of the need to classify safety controls are predominantly inhalation, possibly direct shine and ground shine in certain cases, and slowly-developing dose pathways, such as ingestion of contaminated food, water supply contamination, or particle resuspension, are generally not included. However, quick-release accidents involving other pathways, such as a major tank rupture that could release large amounts of radioactive liquids to water pathways, should be considered as described in the DOE-STD-3009-2014 Section 3.2.4.2. In this case, potential uptake locations should be the evaluation points for radiological dose consequences. This appendix addresses potential dose contributions from water pathways.

These kinds of release to effluent streams can arise in accidents involving liquid process lines, waste tanks, cooling or evaporation systems, primary-to-secondary leakage paths, and other conditions.

Unlike atmospheric releases that typically afford little time (e.g., minutes to hours) to take protective action, aqueous releases to surface bodies typically offer long periods of time (e.g. hours to days) before the general public could be impacted. Consequently, longer times are available in which to take countermeasures.

In most cases, inadvertent release of hazardous material to liquid streams may result in uptake through water ingestion, skin absorption, direct shine from sediments and shore sources, irrigated crop and marine food consumption.

Once released outside the facility boundary, the ultimate disposition of an accidental discharge of liquid effluent from a nuclear facility is highly dependent on volume of release, time period over which the release occurs, soil characteristics in the area around the point of discharge and the configuration of drainage and containment networks, both natural and human-designed, that conduct effluents away from the release point.

Examples include but are not limited to discharge canals, sewers, and viaducts, creeks, rivers, and lakes.

If the surface release interacts with the ground water system in the affected area, the component of discharge into ground water then becomes a long-term risk management problem. Typical time frames for release to human uptake may then range from years to decades for most groundwater cases.

F.1.1 NRC REGULATORY GUIDANCE

The two guiding documents for commercial nuclear licensees are NRC Regulatory Guides 1.109, *Calculation of Annual Doses to* Man *from Routine Releases of Reactor Effluents for the Purpose of Evaluating Compliance with 10 CFR Part 50 Appendix I*, and 1.113, *Estimating Aquatic Dispersion of Effluents from Accidental and Routine Reactor Releases for the Purpose of Implementing Appendix I*. To implement Appendix I of 10 CFR Part 50 ("Numerical Guides for Design Objectives and Limiting

Conditions for Operation to Meet the Criterion 'As Low As Is Reasonably Achievable' for Radioactive Material in Light-Water-Cooled Nuclear Power Reactor Effluents"), the NRC staff developed a series of guides that present methods for calculating effluent releases, dispersion of the effluent in the atmosphere and different water bodies, and the associated doses. In lieu of liquid effluent requirements developed specifically for DOE nuclear facilities, the NRC regulatory guides are summarized below.

Regulatory Guide 1.113: Regulatory Guide 1.113 describes the basic features of calculation models and suggests methods of determining values of model parameters for the estimation of aquatic dispersion of both routine and accidental releases of liquid effluents. General approaches are described for analysis of normal and accident releases into various types of surface water bodies.

Regulatory Guide 1.109: Regulatory Guide 1.109 describes basic features of the dosimetric calculation models and suggests parameters for the estimation of radiation doses to man from effluent releases.

Regulatory Guide 1.113 provides guidance on the use of calculation models and specification of accompanying parametric values to perform aquatic dispersions of routine or accidental releases of radioactive material to a surface body of water. Models for the ground-water pathway are not covered in the guide.

Although specific surface-water models are considered in Regulatory Guide 1.113, representative of models found in the published literature at the time, the stated purpose is using them as a framework for discussing the specific classes of models that they exemplify.

Regulatory Guide 1.113 serves to provide guidance on selection of model types rather than to specify models. The use of models other than those described in the guide is acceptable. For example, the guide notes that tracer release studies conducted in situ can provide accurate predictions as an alternative to modeling.

It is the responsibility of the analyst to choose a specific model, determine values of input parameters, and specify the flow field.

The analyst should fully justify the analytical model chosen and the assumptions employed. With proper justification, it is acceptable for the analyst to use simplified models in conjunction with defensible, conservative inputs and assumptions.

The most bounding type of calculation assumes no dilution of the radiological discharge and a travel time of zero.

In some cases, the predicted doses to human receptors from such a bounding calculation will yield acceptable compliance with respect to regulatory evaluation guidelines. If not, a more realistic transport and dispersion model needs to be employed.

An appropriate model may range from a simplified model with a straightforward, steady-state analytical solution to a complex model requiring a calculation-intensive, time-dependent numerical solution. A suggested practice is to begin with the simplest model that is suitable for the problem and advance towards more comprehensive models as needed to achieve the proper level of results.

The NRC guidance covers a variety of model types that have developed to address discharges into specific types of surface water bodies: non-tidal rivers; estuaries; lakes, reservoirs, and cooling ponds; and open coastal waters.

Dispersal mechanisms accounted for by the various model types include buoyant flow discharge; stream flow and turbulent mixing in rivers; tidal or non-tidal coastal currents in estuaries and coastal waters; and internal circulation or flow-through in lakes, reservoirs, and cooling ponds.

Parameters influencing the transport, dispersion and dilution characteristics include: Direction and speed of the flow currents in the receiving water; Intensity of the turbulent mixing; Size, geometry, and bottom topography of the water body; Location of the effluent discharge in relation to the receiving water surface and shoreline; Amount of recirculation of previously discharged effluent; Characteristics of suspended and bottom sediments; Sediment adsorption properties; and Radioactive decay.

F.1.2 AQUATIC DILUTION MODELS

Classes of models that have been developed for application to the various surface water bodies and covered in the NRC guide are listed in Table F-1.

Table F-1. Aquatic Dilution Models.

Class of Dispersion Model	Model Characteristics	Surface Water Body Application
Stream tube model	Steady-state, two-dimensional, analytical solution	Non-tidal rivers
Transient release model	Transient, two-dimensional, numerical quadrature solution	Non-tidal rivers
Gaussian diffusion model	Steady-state, three-dimensional, analytical solution	Open coastal waters
Transient source model	Transient, two-dimensional, numerical quadrature solution	Open coastal waters
Numerical model	Transient, two-dimensional, numerical solution of conservation equations of mass and momentum	Open coastal waters
Tidally-averaged analytical model	Steady-state, one-dimensional, analytical solution	Estuaries
Tidally-averaged, short-duration analytical model	Transient, one-dimensional, analytical or numerical quadrature solution	Estuaries
Tidally-averaged numerical model	Transient, one-dimensional, numerical solution of constituent transport equation	Estuaries
Intra-tidal numerical model	Transient, one-dimensional, numerical solution of conservation equations of mass,	Estuaries

Class of Dispersion Model	Model Characteristics	Surface Water Body Application
	momentum, and constituent concentration	
Completely mixed model	Transient, homogeneous, analytical solution	Lakes, reservoirs, and cooling ponds
Plug-flow model	Steady-state, homogeneous, analytical solution	Lakes, reservoirs, and cooling ponds
Partially mixed model	Steady-state, homogeneous, analytical solution	Lakes, reservoirs, and cooling ponds
Stratified reservoir lumped parameter model	Steady-state, homogeneous (within stratified layer), analytical solution	Lakes, reservoirs, and cooling ponds
Numerical stratified reservoir models	Transient, one- or two- dimensional, numerical solution of conservation equations of mass, momentum, and constituent concentration	Lakes, reservoirs, and cooling ponds

Environmental Protection Agency (EPA) guidance for water quality-based decisions focuses on programmatic aspects of achieving the water quality goals of the Clean Water Act. The guide also briefly discusses select technical considerations and EPA-supported models. Model characteristics of the various model classes are described, and general guidance on model selection is given.

Models are grouped into the following main categories:

- Temporal characteristics: Steady state (inputs and outputs constant over time); time-averaged (i.e., tidally averaged); and, dynamic (i.e., time-step specification).
- Spatial characteristics: Number of dimensions simulated (1-3); and, degree of spatial resolution (single- or multiple-catchment models).
- Specific constituents and processes simulated (i.e., transport processes; advection; dispersion; density stratification; and, other physics.

Models are also grouped by complexity/computational effort:

- Simple calculator models;
- Steady state computer models;
- Quasi-dynamic models; and,
- Dynamic models.

Four basic steps are identified for the analyst to go through in selecting a model:

- Identify models applicable for the water body type, processes simulated, and type of analysis.
- Define the appropriate level of model complexity needed for the analysis.
- Incorporate practical constraints in to the selection criteria based on data and resource requirements and their availability.
- Select a specific model taking into consideration model familiarity, professional recognition and acceptance of a model, and application ease (i.e., quality of documentation and level of technical support may play important roles in ease of application).

F.1.3 LIQUID EFFLUENT AQUEOUS MODELING RECEPTORS

Onsite receptors are typically not assessed for aqueous releases for other than inhalation, splashing, or shine from spill events. Water ingestion is not addressed, since ingestion of potable water at all site and laboratories is regulated by other state and federal organizations.

Under emergency conditions whereby drinking water supplies have been compromised, it is likely that offsite supplies of water would be transported in to the facility or site in question.

Similar to the consideration of a Maximally-Exposed Offsite Individual (MOI) for airborne releases, the aqueous release pathway is assumed to impact a maximum individual (MI). This is a receptor located at the point of maximum concentration of the effluent stream reaching an offsite (i.e., uncontrolled) location.

Regulatory Guide 1.113 (NRC, 1977) specifies that location of water users, the types of uses, and the usage out to a distance of 50 miles from the site should be established.

F.1.4 DOCUMENTED SAFETY ASSESSMENT APPROACH

Similar to airborne releases, each hypothetical aqueous release assessment should be commensurate to the Hazard Category (HC) of the facility, remaining operational time of the facility, the likelihood of the release, and the complexity of the aqueous pathways for exposure and environmental contamination.

A primary focus should be on process design and operational controls to preclude the potential for aqueous release. In some cases such as storage of liquid wastes or transfer processes involving liquids among processing or stabilization units, this is not feasible. The preferred option in these situations would be to impose engineering barriers or controls to limit the magnitude of the loss of hazardous liquid quantities. Examples of these control types are process sewer networks to conduct liquids to a collection system, and a dam, or berm, to limit the extent of the release such that the material in question remains within facility or site control.

If deterministic design and engineering controls are not entirely effective, and an aqueous event should be considered in the accident analysis phase, then relatively simple engineering calculations should be considered. As noted earlier, most complex surface water models are designed for long-term behavior of contaminants from chronic release conditions. Application of this class of model to hypothetical accident releases reflects undue emphasis on details of the release consequences, rather than eliminating or mitigating precursor conditions.

Nevertheless, if a condition is identified and has an aqueous release consequence, a simple and bounding consequence should be determined. The latter should use low or minimal dilution conditions. In the case of a receiving stream or river for example, this may be a ten-year or other statistical measure of low-flow rate conditions based on a historical perspective. Similarly, the product of the bounding frequency and the conservatively calculated consequence (e.g., dose to the MI) should be well below the applicable EPA criteria.

F.1.5 SURFACE WATER RELEASES

The majority of the following discussion is drawn from two sources: NRC Regulatory Guide 1.113 and NUREG/CR-3332, *Radiological Assessment: A Textbook on Environmental Data Analysis*.

F.1.5.1 INITIAL MIXING

A typical situation for liquid-borne releases is that of a relatively small quantity of contaminant mixed with a relatively large receiving body of water. The initial mixing is based on turbulence from discharge momentum and discharge buoyancy effects. In this phase of the release, effects are relatively concentrated, i.e. occurring over short distances.

Typical dilution effects of one- to two orders-of-magnitude are achieved over 10 to 100 times the characteristic discharge dimension.

The dilution achieved at the end of the initial mixing zone is given by Equation F-1:

$$D = Ci/Co \qquad \textbf{Equation F-1}$$

The initial mixing and dilution regime dominates its longer term, far-field counterpart. The major factors in the initial mixing phase are momentum and buoyancy of the effluent, the outfall location and configuration, and the characteristics of the receiving water, principally the current and depth.

F.1.5.2 FAR-FIELD MIXING

The near-field mixing temporal and spatial scales for mixing of a contaminant will ultimately yield to generally slower transport and diffusion processes of the far-field. In this case, much longer distances and time frames are necessary for achieving appreciable concentration changes.

The time frames are sufficient that radiological and physical transformations may be important, and the magnitude of the receiving water body and its overall advective transport behavior are important concerns.

Radiochemical changes may occur and/or the contaminant may undergo radioactive decay. The principal water bodies and their respective transport characteristics are:

- Rivers: Wide and shallow dimensions marked by strong advective and turbulent flow.
- Estuaries: Several types, marking a transitional zone between water bodies, marked by oscillating tidal flow but weak net transport.
- Small lakes or reservoirs: Strong boundary limitations and weak transport.
- Oceans and large lakes: Large overall extent, and appreciable advection of pollutants.

Depending on the application of the safety analysis, the complexity of models for predicting the concentration of a radiological or chemical species at some point in the far field may range from simple dilution factor considerations, to solving the convection/dispersion equations in one-, two-, or three-dimensions. The latter case is particularly true for river system discharge cases. The selection should be based on the complexity of the system and the requirements of the analysis.

During surface water release events, some constituents may be present as volatilizing liquids or in a dissolved gas form. These contaminants will be released from the liquid-air interface as pressure changes are encountered. A simple approach to predict the release rate, assuming that the radionuclide or chemical is uniformly mixed over the vertical water column H can be calculated by Equation F-2.

$$[dC/dt]_e=K(C-C_s)$$ **Equation F-2**

F.1.5.3 SEDIMENT EFFECTS

As contaminants are transported in a water compartment, the process of adsorption may remove material from the aqueous phase and incorporate material onto sediments.

Both suspended and bed sediments may adsorb contaminants, although suspended sediments are usually more effective on a per unit weight basis. The process is reversible and while the initial reduction of contaminants from water body can be pronounced, over longer periods of time the contaminants can be desorbed or resuspended.

Examples of radionuclides that have been retained in sediments after chronic or acute release near nuclear facilities have been Cs-137 and Pu species.

A counterexample is tritium, which due to the ubiquity of water and hydrogen in the environment shows little evidence of preferential localization in sediments.

The extent to which a radiological species can be adsorbed is referred to as the equilibrium distribution coefficient, or K_d. The equilibrium distribution coefficient is a function of the state of the radionuclide and its concentration, the sediment characteristics, and the nature of the water body.

K_d values are derived from field data and experimentation, and are defined as the amount of contaminant sorbed on sediment/amount of radionuclide left in solution.

F.1.5.4 MODEL ATTRIBUTES

Surface water models for aqueous release conditions should be exercised and applied based on the need of the analysis.

For the most common large water-body release, that of release to rivers or large streams, models have been developed that account for the convection and dispersion effects. The geometrical model should take into account the required complexity necessary to account for change in concentrations. In most situations, one or two dimensions are sufficient; only in rare cases would it be necessary to use three-dimensional modeling. For two-dimensional evaluations, the dependence may be longitudinal-transverse, or longitudinal-vertical, relative to the river/stream flow.

If long-term modeling is necessary to resolve concentration and ultimate fate of hypothetical releases, then attributes of some models to account for particulate transport may be useful. The latter topic includes sediment transport, particulate contaminant transport, and contaminated sediment transport. These transport types are in contrast to solute transport, or the movement of dissolved materials in flowing water. In most computer models, the solute is considered as non-reactive relative to other components of the aqueous environment.

A surface water model can also be linked to uptake mechanisms for evaluation of dose to humans. The most important pathway is water ingestion, but other mechanisms may be of interest including food ingestion (direct from marine foodstuffs, or indirect through use of contaminated irrigation water sources). External exposure is also of importance in some cases, including swimming and other aquatic recreation, or shoreline exposure.

Overkill occurs when the analyst uses a more sophisticated model that is warranted given the available data set or level of results that are required to meet the objectives of the analysis. Misinterpretations can occur when incorrect boundary conditions are specified or the hydrologic history of the site has been misread resulting in a mismatch between the predicted results and the hydrologic history. Inappropriate prediction occurs from either an error in the computer code, a mistake in some data entry, or application of a model to a problem for which it was not designed.

Table F-2 lists the major characteristics to consider in selection of a surface water release model for use in DOE facility accident analysis. NCRP Report No. 76, *Radiological Assessment: Predicting the Transport, Bioaccumulation, and Uptake by Man of Radionuclides Released to the Environment,* warns against three common misuses of models. The key areas include, but are not limited to:

Table F-2. Attributes and Characteristics of Aquatic Dilution Models

Attribute	Characteristics
Release Type	Acute; Chronic
Dimensional dependence	One-; Two-; Three-dimensions
Contaminant Transport	Solute; Particulate
Time Dependence	Steady-state; Dynamic
Solution Technique	Finite Element; Finite Difference
Pathways	Water Ingestion; Food Ingestion and Longer-Term Food chain; Submersion; External Shine and Shoreline Exposure

F.2 OVERVIEW OF AQUATIC DILUTION MODELS

Several models are available for examining the dilution of surface water releases. Five modeling codes are summarized below. In-depth information may be found in the referenced model descriptions.

F.2.1 LADTAP2

NUREG/CR-4013, *LADTAP II: Technical Reference and User Guide*, (LADTAP2) analyzes environmental doses following routine surface water releases of radiological liquid effluents from nuclear facilities. LADTAP2 examines doses to individuals, population groups, and biota via ingestion and external exposure pathways. Calculated population doses provide information for National Environmental Policy Act (NEPA) evaluations and for determining compliance with Appendix I of 10 CFR 50, *Numerical Guides for Design Objectives and Limiting Conditions for Operation to Meet the Criterion 'As Low As Is Reasonably Achievable' for Radioactive Material in Light-Water-Cooled Nuclear Power Reactor Effluents*.

Two model types (i.e., hydrological and exposure pathway) are incorporated within LADTAP2.

One of four hydrological models is chosen to represent mixing in the effluent impoundment system and receiving surface waters. The four model types are direct release to the receiving water, plug-flow, partially mixed, or completely mixed. All but the direct release model account for radiological decay during transit through the impoundment system. Optional models are available to estimate dilution in non-tidal rivers and near shore lake environments.

The exposure pathway model estimates exposure of selected groups at various water usage locations in the environment. Water concentrations at usage locations are related to impoundment system effluent concentrations by a dilution factor and the transit time (allows for radioactive decay during transport). Consequence calculations apply the usage location water concentration to specific pathway models to estimate the resulting exposure.

Examined pathways include ingestion of aquatic foods, irrigated terrestrial food crops, and drinking water (freshwater sites only) and external exposure to shoreline and water sources (boating or swimming).

F.2.2 STREAM2

STREAM2 (Chen, 1998) is an aqueous release emergency response code developed at the Savannah River Site (SRS). STREAM2 models the transport of pollutants from a release point within SRS to various points downstream on the Savannah River.

The model is conservative and assumes a constant river flow, no transport losses, and uniform mixing in stream cross sectional areas. User input includes the time, date, type, location, calculation units, amount, and duration of the release. Input data are used to calculate the pollutant concentrations and transport time at downstream locations, which may be displayed in graphical and tabular form.

The STREAM2 calculation module is an adaptation of the EPA WASP5 code. WASP5 is a water quality analysis program that simulates one-dimensional pollutant transport and fate through surface water.

Additional input files describing the geometry of the pollutant pathway from the release point to the coastal area and the stream/river flow conditions are used in STREAM2 for simulations.

F.2.3 GENII, 2.10.1

GENII-S is an environmental radiation dosimetry software system used to estimate potential radiation doses to individuals and populations (Leigh et. al, 1993). Doses resulting from routine and accidental releases of radionuclides to air and water, and from residual contamination following spills or decontamination operations, can be examined.

GENII 2.10.1is the result of implementing GENII in the Sensitivity and Uncertainty analysis Shell (SUNS) software shell. The SUNS has been developed to simplify the application of Monte Carlo methods of uncertainty analysis to a variety of problems and provides the capability to perform sensitivity and uncertainty analysis in one calculation.

GENII (Napier et al., 1988) is a coupled system of seven programs and the associated data libraries that incorporates the internal dosimetry models recommended by the International Commission on Radiological Protection (ICRP) and allows the user to address the parameters required for scenario generation and data input, internal and external dose factor generators, and environmental dosimetry programs.

GENII 2.10.1analyzes environmental contamination resulting from both far- and near-field scenarios. Annual, committed, and accumulated doses following acute and chronic releases can be calculated. Surface water transport is modeled using the same mathematical models as used in LADTAP2.

F.2.4 RIVER-RAD

RIVER-RAD simulates the transport of radionuclides released to rivers and provides guidance in determining relevant transport mechanisms and key radionuclides for estimating dose (Hetrick, et. al., 1992). RIVER-RAD uses a compartmental linear transfer model divided into reaches (compartments) of equal size, each with a sediment compartment below it. Uniform mixing is assumed within each compartment.

RIVER-RAD models radionuclide transport as a series of transfers between compartments, including the reaches and the water and sediment sub-compartments.

Radionuclide transfer pathways modeled include upward volatilization from the water compartment, movement of radionuclides with the river flow rate, and settling and resuspension. Radioactive decay and decay-product buildup are incorporated into all transport calculations for all radionuclide chains specified by the user. Each nuclide may have unique input and removal rates. Volatilization and radiological decay are considered as linear rate constants in the model.

F.2.5 DISPERS

DISPERS is a collection of mathematical models used for computing the dispersion and fate of routinely or accidentally released radionuclides in surface water and groundwater (NUREG-0868, *A Collection of Mathematical Models for Dispersion in Surface Water and Groundwater*). Five programs, all straightforward dispersion simulations, are included in DISPERS: SSTUBE, TUBE, RIVLAK, GROUND, and GRDFLX.

SSTUBE and TUBE model two-dimensional dispersion of a continuous source into a river after steady state conditions have been established.

RIVLAK also models dispersion within a river, but the source may be steady or unsteady.

GROUND and GRDFLX are used for calculating three-dimensional dispersion within an aquifer. GROUND is most useful for determining the concentration at wells down-gradient of a source released from a vertical plane while GRDFLX considers a horizontal area source.

F.2.6 COMPARISON OF AQUATIC DILUTION MODELS

A comparison of the aquatic dilution models is presented in Table F-3.

Table F-3. Comparison of Aquatic Dilution Models.

Parameter	Model Name				
	LADTAP2	STREAM2	GENII 2.10.11.485	RIVER-RAD	DISPERS
Release type(s)	Routine	Acute	Routine and acute	Routine and acute	Routine or acute
Regulatory Use	NEPA; 10CFR50 Appendix I	Emergency response	Consequence assessment	Dispersion calculations	Dispersion calculations
Model and/or calculation type(s)	Direct release; Plug-flow; Partially and Completely mixed	One-dimensional; WASP5 calculations	LADTAP2 models	Compartmental linear transfer model	Two- & three-dimensional models
Output	Dose, Concentration	Concentration	Dose, Concentration	Concentration	Concentration

F.3 GROUNDWATER TRANSPORT

F.3.1 OVERVIEW

Although radiological and chemical species release to the groundwater compartment can be a concern for operating nuclear facilities, the principal facilities for which groundwater release is a likely pathway are mining and milling operations, and long-term waste disposal areas. Estimates of flow and transport in groundwater are important in assessing the performance of a disposal system because they are probable pathways between hazardous waste and the environment.

The key concepts and models, and developing data to use in these models is outside the intent of the guidance given here, and should be found elsewhere.[75] The relative unimportance is due to the relatively small likelihood of acute release conditions needing to be addressed in the groundwater for most DOE facilities. Additionally, airborne and surface water pathways will tend to dominate the acute phase of accident consideration. However, the ultimate fate of the released contaminants for EIS and other types of safety analysis may need to address the groundwater pathway. The analyst seeking to apply a groundwater model as a tool to assist facility safety analysis should consult other compendia listing more detailed subject information.

F.3.2 GROUNDWATER FLOW AND CONTAMINANT TRANSPORT

Two behaviors need to be captured to model contaminant transport in groundwater media. The first is movement of the carrier fluid and the second is the mass transport of the dissolved contaminants.

In modeling contaminant releases to the groundwater, travel may be in the unsaturated zone above the water table or in the zone of saturation. While flow is for the most part downward in the unsaturated region, flow is predominantly lateral in the saturated zone.

Flow can be governed by many anisotropies in the saturated region depending on the media and layers of sedimentation.

Under the assumption of a homogeneous isotropic medium, the major flow direction can be assumed to follow Darcy's law where the flow volume per unit area is shown in Equation F-3:

$$V_x = -K\, dH/D_x \qquad \textbf{Equation F-3}$$

This relationship assumes the gradient is constant over the increment. The actual velocity of a contaminant would be larger than the flow volume per unit area since water is moving through pore spaces. The pore or seepage velocity U is approximated by dividing the flux term by the effective porosity, as shown in Equation F.4:

$$U = V_x / ne \qquad \textbf{Equation F-4}$$

F.3.3 GROUNDWATER TRANSPORT MODEL CONSIDERATIONS

Recommendations for the use of groundwater models is given by the National Council on Radiation Protection and Measurements, which is an advisory body whose recommendations on radiation protection matters provide the scientific basis for U.S. standards (NCRP Report No. 76). The report summarizes both surface-water and groundwater transport and dispersion models and provides general guidance on their use.

As the simplest and most conservative approach, the safety analyst can assume that no dispersion occurs as the contaminants are transported in the medium of interest, and that the transport velocity is constant.

More complex treatments consider that net convection in one direction and dispersion in all three directions. Furthermore, the dispersion or velocity of transport can vary both spatially and temporally.

[75] This material is excerpted from NUREG/CR-3332.

As the modeling complexity grows, there is a commensurate difficulty in preparing input data and identifying the appropriate sources of information.

The transport of contaminants through the ground can be estimated using tracers, groundwater dating, or mathematical modeling. Mathematical modeling involves solving equations of mass transport for the carrier fluid (water) and for the dissolved constituents (radionuclides).

In applications involving high-level waste repositories, an additional equation for heat transport is required, but models for applications of this type are outside the scope of the report. Results are obtained from the transport equations through simplifying approximations that allow analytical (closed-form) solutions or through numerical methods.

Numerical solutions generally employ one of following three solution techniques: finite differences (FD), finite elements (FE), or network analysis.

Numerical methods generally require an extensive input data set. The availability of this data needs to be considered by the analyst as the lack of required data may make sophisticated numerical modeling impractical.

APPENDIX G ADDITIONAL CONSIDERATIONS FOR RADIOLOGICAL CONSEQUENCES

G.1 DOSE EVALUATIONS

The effects of exposure to ionizing radiation were originally defined in terms of the amount of ionization in air produced by gamma radiation and x-rays. The unit used was the Roentgen (R), now defined as the ratio $\Delta Q/\Delta m$, where ΔQ is the sum of all charges of one sign produced in air when all the electrons liberated by photons in a mass Δm of air are completely stopped in air. It is equal to 2.58E-04 coulombs produced in 1 kg of air. This is equivalent to 1.61E+15 ion-pairs produced per kilogram of air, or an energy deposition of 87.3 ergs/g of air (Turner,1986). Absorption of 1 R of radiation in tissue corresponds to about 95 ergs/g of tissue; this unit is called the roentgen-equivalent, physical (rep). The rep is no longer used.

Today, dose is expressed (1) as an absorbed dose, that is, the amount of energy deposited in matter, or (2) as an equivalent dose, a measure of damage done in tissue. The traditional unit of absorbed dose is the rad (radiation absorbed dose) and is defined as 100 ergs absorbed in 1 g of material, slightly greater than the outdated rep. The newer standard international unit is the gray (Gy), which is defined as 1 J absorbed in 1 kg of material. Thus, 1 Gy = 100 rad. This equality applies to any type of radiation absorbed in any type of material.

The dose of most interest in accident analysis is the equivalent dose, as this is a measure of the biological damage. The amount of damage depends upon the type of radiation as well as the amount of energy absorbed. The equivalent dose H_T to a particular tissue T is equal to the absorbed dose D_T in that tissue times a radiation-weighting factor w_R

$$H_T = w_R D_T \qquad \textbf{Equation G-1}$$

where w_R is a measure of the amount of damage done by the radiation.[76] If more than one type of radiation impacts the tissue, H_T is calculated by summing over all radiation types. Table G- gives the radiation weight factors (ICRP 1991) for the four radiation types considered here.

[76] The definitions given here are taken from the *1990 Recommendations of the International Commission on Radiological Protection* (ICRP-60, 1991). In earlier recommendations of the ICRP, the terminology was a little different. The following table gives the old and new terminology. The old terminology is still in use.

Old Terminology	New Terminology
Quality Factor	Radiation Weighting Factor
Dose Equivalent	Equivalent Dose
Committed Dose Equivalent	Committed Equivalent Dose
Effective Dose Equivalent	Effective Dose
Committed Effective Dose Equivalent	Committed Effective Dose

The effective dose is not identical to the effective dose equivalent in that the organ weighting factors are slightly different and the organs included in “remainder” are different. A similar statement can be made for the differences between committed effective dose and committed effective dose equivalent.

Table G-1. Radiation Weighting Factors

Type, Energy Range		Radiation Weighting Factor, w_R
Alpha	any energy	20
Beta	any energy	1
Gamma	any energy	1
Neutrons	< 10 keV	5
	10 keV to 100 keV	10
	>100 keV to 2 MeV	20
	>2 MeV to 20 MeV	10
	> 20 MeV	5

The traditional unit for equivalent dose is the rem (roentgen-equivalent, man). The newer international unit is the sievert (Sv). The relation between them is the same as between gray and rad (1 Sv = 100 rem). Sometimes the unit centisieverts (cSv) is used in place of rem.

Example: Assume a medical x ray gives the lungs an absorbed dose of 20 rad (0.2 Gy). The equivalent dose would be 20 rem (0.2 Sv), as x-rays are similar to gamma rays and have a radiation weighting factor of one. On the other hand, if the absorbed dose of 20 rad to the lungs were from inhalation of plutonium, an alpha emitter, the equivalent dose would be 400 rem (4 Sv), as the radiation-weighting factor for alpha radiation is 20.

The radiation-weighting factor is related to the stopping power of the material, expressed as Linear Energy Transfer (LET):

$$LET = dE/dx \qquad \textbf{Equation G-2}$$

where dE is the average energy locally imparted to the medium by a charged particle traversing the distance dx. Alpha and beta particles have high and low LET, respectively. Gamma radiation, although not a charged particle, is considered equivalent to low LET radiation. Neutrons have a moderate to high LET, depending upon their kinetic energy.

The definition of equivalent dose does not differentiate between short-term and long-term dose, or between external and internal exposure. A related term is committed equivalent dose (CED), which is the predicted dose from internal exposures over the remaining life of the individual, normally taken to be 50 years for adults (such as workers) or 70 years for children (as in the general population); it does not include external exposures. The CED is thus a subset of the equivalent dose. This has led to some confusion as it has led some to incorrectly use equivalent dose exclusively for external radiation, apparently as a counterpoint to committed equivalent dose, which is used exclusively for internal radiation. A new term, total organ dose equivalent (TODE), is now used to indicate the sum of the external (short-term) and internal (committed, long-term) doses to an organ or tissue (CFR 1991).

Doses are also calculated for the body as a whole. This is done by summing over all organs the product of an organ weighting factor and the equivalent dose for that organ. This sum is called the effective dose,

formerly called the effective dose equivalent (EDE), a term still used. The organ weighting factors represent the fraction of the total health risk resulting from uniform whole body irradiation that could be attributed to that particular tissue or organ; these factors are between zero and one; their sum over all organs and tissues is one. The weighting factors for the various organs are shown in Table G-, as taken from *Recommendations of the International Commission of Radiological Protection* , (ICRP-60, 1991); for comparison, *Recommendations of the ICRP* (ICRP-26, 1977) values are also shown, as they may still be used for existing safety analyses in nonreactor nuclear facility DSAs.

Table G-2. Organ Weighting Factors

Organ	Organ Weighting Factor	
	ICRP-26	ICRP-60
Bladder	–	0.05
Bone Marrow (red)	0.12	0.12
Bone Surface (skeleton)	0.03	0.01
Breast	0.15	0.05
Colon	–	0.12
Esophagus	–	0.05
Gonads	0.25	0.20
Liver	–	0.05
Lung	0.12	0.12
Skin	–	0.01
Stomach	–	0.12
Thyroid	0.03	0.05
Remainder	0.30	0.05

Example: Assume every organ listed in Table G- (considering “remainder” as a single organ) receives a dose of 1 rem each. The effective dose to the whole body would then also be 1 rem. On the other hand, if the bone surface was to receive 100 rem (1 Sv) and all other organs received none, the effective dose would again be 1 rem, using the ICRP-60 organ weighting factors. This example is for illustration only as no accident would give dose to only one internal organ.

A term similar to effective dose is committed effective dose (formerly, the committed effective dose equivalent—CEDE, a term still used), which is the predicted dose from internal exposures over the remaining life of the individual, normally taken to be 50 years for adults, or 70 years for children; it also does not include external exposures. Committed effective dose is thus a subset of effective dose. However, as with equivalent dose *cf.* committed equivalent dose, confusion has arisen in that some incorrectly use effective dose to refer to only external radiation, because committed effective dose refers only to internal radiation. A new term, total effective dose equivalent (TEDE), is now used to indicate the sum of the external (short-term) and the internal (committed, long-term) effective doses (CFR 1991).

G.2 HEALTH RISKS

Although not required for the DSA accident analysis to determine the need for safety class (SC) or safety significant (SS) controls described in Chapter 2, radiological doses may be converted to health risks for other special assessments, such as comparison to the DOE Safety Goal in DOE Policy P 420.1, *Department of Energy Nuclear Safety Policy*. Once doses have been calculated, the corresponding health risks can be determined. This is done by multiplying doses by stochastic risk factors. Latent cancer fatalities (LCFs) are the (chronic) health risks of most interest. The term "latent" indicates that the estimated cancer fatalities would occur sometime in the future, within the next 50 years for adults, or the next 70 years for the general population, which includes children. One can also estimate latent cancer occurrences (fatal plus non-fatal), genetic effects, etc., but these are not normally evaluated in safety analyses. The stochastic risk factor depends upon the type of radiation and the organ considered.

G.2.1 HIGH-LET RADIATION

In the case of alpha emitters, such as plutonium and uranium, the only organs of importance for cancer risk are the lungs, liver, and bone surface (Abrahamson, 1993). The stochastic risk factors for cancer fatalities for these organs are shown in Table G-. For these three organs, the stochastic risk factors are linear and continuous. Earlier models, based on ICRP-26 (1977), used a linear-quadratic model. The new model, based on *Recommendations of the International Commission of Radiological Protection* (ICRP-60, 1991), is linear but may be discontinuous for some radionuclides. The values from *Health Effects Models for Nuclear Power Plant Accident Consequence Analysis, Modification of Models Resulting From Addition of Effects of Exposure to Alpha-Emitting Radionuclides* (Abrahamson, 1993) differ from the earlier ones (ICRP-26): the lung factor is about four times larger, the bone skeleton factor is about ten times smaller, and liver is about three times smaller than the earlier values. The values in Table G- are for high-LET radiation (alpha particles). Table G- does not give the stochastic risk factor for committed effective dose, as the total cancer risk should be calculated as the sum of the individual organ cancer risks [Σ (dose × stochastic factor)]. The other organs of the body do not contribute significantly to cancer risk from exposure to alpha radiation and have been ignored.

Table G-3. Stochastic Risk Factors for Alpha-Emitters (Abrahamson, 1993).

Organ	**Risk Factor** (LCF/rem)
Bone surface	6.0×10^{-7}
Lungs	8.0×10^{-5}
Liver	1.5×10^{-5}

Example: A calculation of committed inhalation doses to a certain receptor from a release of Pu-239 gives a bone-surface dose of 0.35 rem, a lung dose of 0.11 rem and a liver dose of 0.079 rem; the effective dose (whole body) was 0.035 rem. The effective dose includes contributions from all organs, not just the three mentioned here. For this individual, the LCF risk would therefore be:

$$(0.35)(6.0E\text{-}07) + (0.11)(8.0E\text{-}05) + (0.079)(1.5E\text{-}05) = 1E\text{-}05 \text{ LCF}.$$

This means that only one person in 10^5 would be predicted to die of cancer at some future time from this exposure. Note that although the bone dose is larger than the doses to the other organs, the lung dose is more important in terms of cancer risk, as seen in this example.

G.2.2 LOW-LET RADIATION

For low-LET radiation (beta and gamma radiation), the latent cancer risk is normally calculated from the CED, although the individual organ cancer risks could also be summed. ICRP-60 (1991) recommends using a stochastic risk factor of 5E-04 LCF/rem (5E-02 LCF/Sv) for the whole population, or 4E-04 LCF/rem (4E-02 LCF/Sv) for adult workers, based on the committed effective dose. (The factor for the public is higher than for adult workers because the public consists of a mixture of individuals with varying degrees of resistance to hazardous materials, including children, the elderly, and the infirm. This includes the cancer risk to all organs, unlike the treatment of alpha radiation, which considers only the three organs of Table G- to be important for cancer risk.) This ICRP-60 recommendation has been adopted by the Environmental Protection Agency (EPA) for the evaluations of Environmental Assessments (EAs) (NEPA, 1993). Had this factor been used in the above example, the LCF risk to that individual would have been (0.0351) (5E-04) = 1.75E-05 LCF, or about 75 percent higher than obtained from using Table G- data. This low-LET risk factor is not recommended for alpha-emitters (high LET).

G.2.3 ACUTE HEALTH RISKS

Doses received in a short period (acute doses) may cause acute health risks, if large enough. A dose from gamma or neutron radiation, such as from a criticality, is the primary concern. Table G-4 (adapted from Turner, 1986)) summarizes the health effects associated with varying levels of gamma radiation.

Table G-4. Acute Radiation Effects for Gamma Radiation.

Dose (rad)	Health Effect
0–25	No detectable effect
25–100	Some biological damage; recovery probable
100–300	More damage; recovery probable but not assured
300–600	Fatalities occur in about half the population
> 600	Death expected

An acute, whole-body, gamma-ray dose of about 450 – 500 rad would probably be fatal to about half the population within about 30 days. This dose is known as lethal dose 50 (LD_{50}), sometimes called $LD_{50/30}$. Because gamma radiation has a radiation-weighting factor of one as shown in Table G-, the doses in Table G- could also have been labeled in rem. Presumably, neutron doses, in rem, would give similar effects.

An acute dose from inhalation of plutonium or uranium, the dose received in a few hours or days, is normally very small. All of the isotopes of plutonium and uranium have half-lives of many years; therefore, the inhalation dose received by a person during the first few days following inhalation will only be a tiny fraction of the lifetime dose. Accordingly, an acute health effect requires a very large amount of plutonium to be released. For example, in order for a person at a distance of about 2 km from the release site to get a dose large enough to cause pneumonitis, the first prompt health effect to occur, an airborne release of about 100 kg of respirable plutonium would be required (Peterson, 1993). Such a large release is not physically possible. Therefore, acute health effects need not be considered for releases of plutonium or uranium.

APPENDIX H AEROSOL FORMATION, EVAPORATION, AND MASS ENTRAINMENT

Section 7.5 of this Handbook briefly addressed some of the complexities associated with toxic chemical release phenomenology. This appendix provides additional information to the analyst on how to calculate chemical source terms from the following release phenomenology:

- Two-phase flow (i.e., flashing and aerosol formation) from stored pressurized liquids that are suddenly released (see Section 7.5.1);
- Release of a pressurized gas from a vessel (see Section 7.5.2); and,
- Pool boiling (i.e., evaporation) from the non-flashed portion of the pressurized liquid release or non-pressurized liquid releases (see Section 7.5.4).

Additional information associated with energetic events, briefly discussed in Section 7.5.5, is provided in Appendix B, Fires, and Appendix C, Explosions. Dense gas dispersion is treated in its entirety in Section 7.5.3.

H.1 ELEMENTS OF AEROSOL FORMATION MODELING

H.1.1 FLASHING FRACTION AND AEROSOL FORMATION

The flashing fraction may be calculated by means of a heat balance across the outlet orifice where the decrease in latent heat of vaporization and increase in heat capacity are accounted for as the initial temperature approaches the critical temperature. This fraction is expressed as shown in Equation H-1.

$$f = 1 - exp^{-2.63 \frac{c_l(T_b)}{L(T_b)}(T_c - T_b)\left\{1 - \left[\frac{(T_c - T_l)}{(T_c - T_b)}\right]^{0.38}\right\}} \qquad \textbf{Equation H-1}$$

Where,

f	=	flashing fraction (dimensionless);
$C_l(T)$	=	liquid heat capacity at temperature T (J/kg·°K);
L(T)	=	latent heat of vaporization at temperature T (J/kg);
T_c	=	critical temperature (°K);
T_b	=	liquid boiling temperature at one atmosphere pressure (°K); and,
T_l	=	liquid temperature (°K).

Generally, a superheated liquid jet or spray needs to be present to achieve significant quantities of liquid droplets suspended in the initial cloud. As the discharge pressure decreases, some of the liquid will flash immediately to vapor, while the remaining non-flashed liquid will either be suspended as liquid droplets (i.e., finely distributed aerosols), or fall to the ground forming a pool that will boil or evaporate over time.

The distribution of droplet sizes is required before the rainout fraction can be calculated. Kitamura et al. (1986) and Bettis (1987) have experimentally observed that the droplet sizes are log-normally distributed, as shown in Equation G-2.

$$p(d) = \frac{exp^{\frac{1}{2}\sqrt{[\ln(d) - \ln(<d>)]/\ln(\sigma_g)}}}{\sqrt{2\pi}\ \ln(\sigma_g)\ d}$$

Equation H-2

Where,

d	=	random droplet diameter (m);
p(d)	=	probability distribution as a function of drop diameter d (dimensionless);
σ_g	=	geometric variance (dimensionless) (assume σ_g=1.3; Iannello et. al., 1989); and,
<d>	=	mean droplet diameter (m).

The mean droplet diameter may be estimated by means of the Nukiyama-Tanasawa equation (see Tilton, 1990), as shown in Equation H-3.

$$< d > = 585 \frac{\sqrt{\sigma_l}}{u_e \sqrt{\rho_l}}$$

Equation H-3

Where,

σ_l	=	liquid surface tension (dyne/cm);
ρ_l	=	droplet liquid density (kg/m^3); and,
u_e	=	axial spray velocity at end of discharge region (m/s),

where the droplet diameter is μm units. Using the values for each of the salient parameters germane to anhydrous chlorine yields, a droplet diameter distribution is obtained.

Since an instantaneous release directly into the ambient wind field is postulated for this analysis, the axial spray velocity is assumed identical to the ambient wind speed. The criterion for droplet rainout is satisfied when the inclination of the droplet trajectory, β_d, with respect to the vertical direction is greater than the half angle of jet expansion at the start of entrainment. The subsequent droplet settling velocity (V_d) may be calculated by solving the balance equation expressing the equality between the force of gravity on the droplet and the upward-acting viscous and drag forces, as depicted in Equation H-4.

$$\frac{\pi}{6} d^3 (\rho_l - \rho_g) g = C_d \rho_g \frac{V_d^2}{2} \left(\frac{\pi}{4} d^2 \right)$$

Equation H-4

With,

ρ_g = vapor density after expansion (kg/m^3); and,

C_d = friction factor including both viscous and drag losses (dimensionless).

Where, Equations H-5 and H-6 show:

$$C_d = \frac{24}{Re_d} + \frac{6}{1+\sqrt{Re_d}} + 0.4$$

Equation H-5

$$Re_d = \frac{\rho_g V_d \; d}{\mu_g}$$

Equation H-6

Where, μ_g denotes the viscosity of vapor in units of Pa·s.

Therefore, the final expression which V_d satisfies is given by Equation H-7.

$$3V_d \left[\frac{24\,\mu_g}{\rho_g V_d\, d} + \frac{6}{1+\sqrt{\frac{\rho_g V_d\, d}{\mu_g}}} + 0.4 \right] - 4\,d\,(\rho_d - \rho_g)\,g = 0$$

Equation H-7

The critical droplet diameter (d_c) satisfies the criterion in Equation H-8:

$$\tan\beta_{d_c} = \frac{V_{d_c}}{U_e} = \tan\beta_e$$

Equation H-8

Any droplet trajectory possessing an angle of inclination, β_d, with respect to the horizontal that is greater than the spray half-angle, β_e, will drop out of the vapor-aerosol plume and rainout onto the ground surface to form a pool. Observing that as V_d increases, tan β_d also increases for u_e>0 fixed, and the solution is therefore unique and given by Equations H-9 and H-10:

$$V_{d_c} = U_e \tan\beta_e$$

Equation H-9

$$f'(d_c) = 3V_{d_c}\left[-\frac{24\mu_g}{\rho_g V_{d_c} d_c^2} + \frac{3\sqrt{\rho_g V_{d_c}}}{\sqrt{\mu_g d_c}\left(1+\sqrt{\frac{\rho_g V_{d_c} d_c}{\mu_g}}\right)^2}\right] - 4(\rho_d - \rho_g)g$$

Equation H-10

Finally, the solution to d_c may be obtained using Newton's method by way of the two functional relationships in Equation H-11:

$$f(d_c) = 3V_{d_c}\left[\frac{24\mu_g}{\rho_g V_{d_c} d_c} + \frac{6}{1+\sqrt{\frac{\rho_g V_{d_c} d_c}{\mu_g}}} + 0.4\right] - 4d_c(\rho_d - \rho_g)g = 0$$

Equation H-11

Using a model for a spherical droplet in laminar flow, which is not to be confused with turbulent jet flow during droplet formation, a critical drop diameter, d_c, can be calculated.

Droplets possessing a diameter exceeding this value experience a sufficiently large gravitational force to induce the beginning of rainout. Using a value of β_e=9.1° (Wheatly, 1987), the critical drop diameter has been determined to be 25 microns. The fraction of liquid that rains out, f, is then calculated implicitly from Equations H-12 and H-13.

$$f_p = 1 - \int_{-\infty}^{d_c} p(\xi)\,d\xi$$
$$= \tfrac{1}{2}\left[1 - erf\left(X_c/2\right)\right]$$

Equation H-12

Where,

$$X_c = \frac{\ln(d_c) - \ln(<d>)}{\ln(\sigma_g)};$$
$$erf(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-\xi^2}\,d\xi$$

Equation H-13

In this case, since f_p=0.05, essentially all of the aerosol component remains airborne and evaporates right above the pool as the aerosol particles are transported downwind.

It should be noted that a great deal of uncertainty lies in the estimate of exactly how much of the non-flashed liquid is entrained into the air as a suspended aerosol. Large-scale experiments indicate that the

mass of aerosol produced is very roughly equal to the mass of superheated liquid which immediately flashed to vapor when the flashing fraction is less than one-third (Lees, 1986). Since the flashing fraction is below one-third for the chlorine release, the initial aerosol mass is assumed to be equal to the mass of liquid flashed to vapor.

When the release initially results in a dense gas slumping cloud, it is important to note that the dispersing medium within the dense gas cloud consists only of the sub-cooled vapor (i.e., vapor evaporated from the pool) component. No clear causal relationship exists between the dense cloud and droplets of liquid raining out of the cloud. Therefore, the model treats these two phenomena separately; specifically the mass fraction of the release which remains suspended as aerosol, and that which falls onto the ground to form a boiling or evaporating pool. A portion of the remaining liquid will either be suspended as liquid droplets or finely distributed aerosol. Any liquid entrained into the vapor cloud as a suspended aerosol is characterized in terms of the liquid mass evaporation rate and temperature as a function of time.

The suspended liquid aerosol droplets evaporate as the ambient air flows past them. The computational model of Papadourakis, Caram and Barner (1990) is applied to determine the rate at which a droplet of 1000-micron diameter would evaporate in an ambient wind of 5 mph (2.22 m/s) and a temperature of 100°F (37.8°C), using an initial spray velocity of approximately 12 m/sec. A 1,000-micron diameter particle was selected since it represents a 95 percent confidence bound on aerosol particulate size (i.e., only 5 percent of aerosol droplets formed are expected to have a diameter greater than 1,000 microns for a typical droplet spectrum).

Details of the underlying equations in the model describing the conservation of mass, energy and momentum are not included in this discussion as they are beyond the scope of this Appendix. The final numerical results demonstrate that the entire droplet mass undergoes complete evaporation within 12.25 m of the liquid release point. Therefore, as a conservative and bounding simplifying assumption, the analyst can assume that all-aerosol component evaporates in the near vicinity of the residual liquid pool with no initial dilution and the mass of vapor is then added to the vapor source term.

H.1.2 TWO-PHASE RELEASE OF CHLORINE FROM A PIPE

In this example, there is conversion of some of the chlorine liquid to vapor within the pipe itself. This change in upstream composition subsequently causes a reduction in the mass release rate and an increase in outflow velocity.

The variation in these release parameters can be calculated from Equation H-14, which is the Fauske equation found in *Loss Prevention in the Process Industries* (Lees, 1996):

$$G = A_e \left[\frac{-k}{T_1 + T_2 + T_3} \right]^{1/2}$$ **Equation H-14**

Where,

$$T_1 = (1 - x + kx)\, x\, dv_g / dP$$ **Equation H-15**

$$T_2 = \left[v_g (1 + 2kx - 2x) + v_l (2kx - 2k - 2xk^2 + k^2) \right] dx / dP$$ **Equation H-16**

$$T_3 = k\left[1 + x(k-2) - x^2(k-1)\right] dv_1 / dP$$ **Equation H-17**

$$dx / dP = -\left(dh_f / dP + x dh_{fg} / dP\right) / h_{fg}$$ **Equation H-18**

Where,

G = release rate (kg/s);

A_e = effective area of the orifice (m^2);

x = mass fraction of vapor in the mixture (dimensionless);

v_g = specific volume of the gas (m^3/kg);

v_l = specific volume of the liquid (m^3/kg);

k = $(v_g/v_l)^{1/2}$

P = saturation pressure (Pa);

h_f = enthalpy of the saturated liquid (cal/g); and,

h_{fg} = latent heat of vaporization (cal/g).

The equation was evaluated using an Antoine relationship (Reference) for saturated vapor pressure and ideal gas conditions were assumed. Table H-1 presents the results which show the percentage of gas mass fraction. The percentage of liquid mass fraction is defined as 1 - gas mass fraction.

Table H-1. Calculated Variation of Chlorine Jet Release Parameters as a Function of Upstream Gas Mass Fraction (Mills And Paine, 1990).

Gas Mass Fraction	Mass Release Rate (kg/s)	Release Velocity (m/s)	Initialization Temperature (degrees K)	Density (kg/m^3)	Effective Droplet Diameter (mm)
0.1	81.8	71	239	11.8	0.352
0.2	63.3	101	239	9.2	0.295
0.3	51.8	120	239	7.5	0.270
0.4	43.8	134	239	6.3	0.256
0.5	38.0	144	239	5.5	0.247
0.6	33.6	152	239	4.8	0.241
0.7	30.1	158	239	4.3	0.236

Gas Mass Fraction	Mass Release Rate (kg/s)	Release Velocity (m/s)	Initialization Temperature (degrees K)	Density (kg/m^3)	Effective Droplet Diameter (mm)
0.8	27.3	163	243	3.9	0.233
0.9	24.9	167	???	3.6	0.231

The table shows that the mass release rate is inversely proportional to the gas mass fraction and the release velocity is proportional to the gas mass fraction. As the fraction of the fluid in the pipe that flashes from liquid to gas at the outlet increases, choked flow upstream in the pipe results, and the resultant mass release rate decreases. This is a very interesting case where pressurized liquid two-phase flow from a pipe also exhibits pressurized gas choked flow characteristics.

H.2 ANALYTICAL METHODS FOR GAS OUTFLOW CALCULATIONS

The Environmental Protection Agency (EPA) Risk Management Plan (RMP) Offsite Consequence Assessment (OCA) guidance presents a method for estimating the maximum emission rate for an unmitigated release of gas from a vessel; see Section 8.1.1, Equation 11 of the RMP OCA. The expression does not account for the decrease in the release rate as the pressure in the tank decreases. One method for determining the time-dependent mass release rate from a pressure vessel follows.

H.2.1 TIME-DEPENDENT VESSEL GAS BLOW DOWN MODEL

In the case where the onset of gas release occurs under choked, or sonic, flow conditions, the time-dependent mass release rate is given by

$$w(t) = w_{\mathrm{o}}\,[\mathrm{F}(t)]^{(\gamma+1)/(\gamma-1)}$$ **Equation H-19**

Where,

t time [s];

w sonic mass release rate [kg/s];

w_{o} is the initial sonic mass release rate [kg/s] given by

$$\mathrm{w}_{\mathrm{o}} = C_{\mathrm{d}} A_{\mathrm{d}} \sqrt{\gamma \rho_{\mathrm{o}} P_{\mathrm{o}}\,[2/(\gamma+1)]^{(\gamma+1)/(\gamma-1)}}$$ **Equation H-20**

C_{d} coefficient of discharge [dimensionless];
A_{d} outlet (orifice) area [m^2];
g specific heat ratio [dimensionless];
r_{o} initial fluid density inside the vessel [kg/m^3];
P_{o} initial fluid pressure inside the vessel [Pa].

The time dependent function in the relationship, F(t), is given by Equation H-21, below:

$$F(t) = 1/(1+At) \qquad \textbf{Equation H-21}$$

Where,

$$A = w_o(\gamma - 1)/2m_o \qquad \textbf{Equation H-22}$$

and,

m_o represents the initial mass inside the vessel (kg).

Equation H-19 is valid only for the conditions of choked (i.e., sonic) flow, namely when the internal system pressure, P_o, exceeds a physical constant referred to the critical pressure $P_{critical}$ defined as:

$$P_{critical} = P_{ambient}\left(\frac{\gamma+1}{2}\right)^{\gamma/(\gamma+1)} \qquad \textbf{Equation H-23}$$

Where, $P_{ambient}$ is the ambient pressure outside of the vessel.

<u>Note:</u> $P_{critical}$ should not be confused with the critical pressure, P_c, associated with the critical point on a temperature-volume diagram for a particular substance.

Although most of the tank inventory will be discharged in sonic flow, it is possible to calculate the time at which the flow becomes subsonic or unchoked. Assuming ideal gas behavior, the initial mass release rate from the vessel under unchoked (i.e., sub-sonic/sub-critical) flow conditions when $P_o \leq P_{critical}$ is given by Equation H-24, taken from Perry (1984):

$$m_r(0) = A_d C_d \left\{ 2\frac{P_{ambient}^{2/\gamma}}{P_o^{1-2/\gamma}} \rho_v \frac{\gamma}{\gamma+1}\left[1 - \left(\frac{P_{ambient}}{P_o}\right)^{(\gamma-1)/\gamma}\right]\right\}^{1/2} \qquad \textbf{Equation H-24}$$

Where,

$m_r(0)$ = gas mass release rate at time zero [kg/s];
M_w = gas molecular weight [kg/kg·mole]; and,
P_o = gas pressure upstream of the orifice [Pa].

Where, r_v denotes the vapor density [kg/m^3] at standard temperature and pressure. Again, Equation H-24, just as in the case of w_o appearing in Equation H-19, is an expression of the maximum mass release rate under their respective release regimes.

Alternatively, the following time-dependent expression for the mass outflow may be used to obtain the average mass release rate:

$$m_r(t) = \frac{A_o C_o P_o}{Z\,R\,T_o}\left[1 + \tau\left(\frac{\gamma - 1}{2}\right)\left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}\right]^{2\gamma/(1-\gamma)}$$

Equation H-25

Where,

$$\tau = \frac{A_o}{V}\left(\gamma\,R\,T_o\right)^{1/2} t$$

Equation H-26

and,

t = time following the beginning of unchoked flow [s],
Z = compressibility factor [dimensionless];
R = gas constant [8314.39 N/m·kg-mole·^{o}K];
T_o = gas temperature upstream of the orifice [^{o}K];
V = internal tank volume [m^3].

The *average* vapor release rate, $E\,\{m_r(t)\}$ in the time period $[0,T]$ is then computed by evaluating Equation H-27.

$$E\left\{m_r(t)\right\} = \frac{1}{T}\int_0^T m_r(t)\,dt$$

$$= \frac{2\,A_o\,C_o\,P_o}{Z\,R(1+\gamma)T_o}\left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{2(\gamma-1)}}\left\{1 - \left[1 + \frac{A_o}{V}\left(\gamma R T_o\right)^{1/2} T\left(\frac{\gamma-1}{2}\right)\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}\right]^{2\gamma/(1-\gamma)}\right\}$$

Equation H-27

The expressions presented above for the vapor mass rate of outflow are applicable only to tanks where the inner diameter is much greater than the diameter of the outlet orifice. If the analysis involves leakage from a length of process pipe, then the model described below should be used to estimate the vapor mass outflow rate.

H.2.2 VAPOR OUTFLOW FROM BREACH OF A PIPELINE

The time-varying release rate of gas or vapor from a pipeline rupture is estimated using the following expression (Bell, 1978; Wilson, 1979):

$$m_r(t) = \frac{m_r(0)}{1+\alpha_p} e^{-\frac{t}{(\alpha_p^2 \beta_p)}} + \frac{W_o}{\beta_P} e^{-\frac{t}{\beta_p}}$$

Equation H-28

Where,

$m_r(t)$ = gas mass release rate at time t [kg/sec];
t = time since the pipeline rupture [sec];
W_o = total mass of gas in the pipe length [kg]; and,
b_p = a constant expressed as

$$\beta_p = 2(\gamma f)^{1/2} L^{3/2} / (3 v_o D^{1/2})$$

Equation H-29

f = pipe friction factor [dimensionless];
D = pipe diameter [m];
L = pipe length [m]; and,
v_o = speed of sound in the pipeline gas [m/s]

$$v_o = (\gamma R T_f / M_w)^{1/2}$$

Equation H-30

T_f = final temperature of gas release just after leaving the orifice [^{o}K];
a_p = dimensionless parameter given as:

$$\alpha_p = W_o / [\beta_p m_r(0)]$$

Equation H-31

W_o = total initial mass of gas [kg] given by

$$W_o = \pi D^2 P_o L M_w / (4 R T_o)$$

Equation H-32

The variable T_f represents the final temperature of the gas as it first accelerates towards the sonic velocity at the orifice, and then decelerates after passing into the atmosphere. If the gas is assumed to exhibit ideal behavior, there will be no Joule-Thompson cooling; hence $T_f = T_o$.

To calculate the *average* vapor release rate, $E\{m_r(t)\}$, in the time period $[0,T]$, use Eq. H-33 below.

$$E\{m_r(t)\} = \frac{1}{T}\int_0^T m_r(t)\, dt$$

$$= \frac{m_r(0)\, \alpha_p^2\, \beta_p}{T\left(1+\alpha_p\right)}\left(1 - e^{-\frac{T}{(\alpha_p^2 \beta_p)}}\right) + \frac{W_o}{T}\left(1 - e^{-\frac{T}{\beta_p}}\right)$$

Equation H-33

When loss of liquid containment results from a localized breach in a self-contained storage vessel, the mass flow rate of liquid out of the orifice may be computed as a function of the upstream pressure. This time-dependent pressure term, in turn, depends on:

- Vapor partial pressure;
- Hydrostatic head above the leak; and,
- Pressure head induced externally by a mechanical device such as a compressor.

Assuming that the system pressure input to the code, P_{sys}, reflects the pressure head from the compressor, the first two pressure terms may be calculated. An upper bound on the release duration may be obtained by neglecting terms (1) and (3), which permits some reasonable values for the time intervals to be established.

H.2.3 OUTFLOW FROM A CYLINDRICAL TANK

The time-dependent mass flow rate of an incompressible fluid out of an upright cylindrical tank can be derived. Beginning with the Bernoulli equation expressed in the form:

$$\frac{\Delta u_b^2}{2} + g\,\Delta z + \frac{\Delta p}{\rho} = 0\,,$$

Equation H-34

Where, in the MKS system, g_c becomes (kg)(m)/(N)(sec^2) or $g_c \equiv 1$, and g denotes the local value for the acceleration of gravity. The variables u_b, z, r, and P represent the fluid bulk speed, fluid free surface elevation above ground level, fluid density, and pressure experienced at the orifice centerline, respectively.

<u>Note:</u> Dz denotes the distance between the fluid free surface level within the tank and the orifice elevation above ground, and by the convention chosen, the D operator represents the difference in going from the interior of the vessel to the outer ambient environment. For the sake of simplicity, it is assumed that internal and external pressure terms remain constant throughout the release duration. Therefore:

$$\Delta u_b = u_{b_{inside}} - u_{b_{outside}}$$
$$\Delta z = z - z_o$$
$$\Delta p = p_{inside} - p_{outside} = p_{system} + p_{vapor} - p_{ambient}$$

Equations H-35 through H-37

with the orifice elevation denoted by z_o and the system pressure, saturated vapor pressure, and ambient pressure represented by P_{system}, P_{vapor}, and $P_{ambient}$, respectively.

Further assuming that u_b within the tank as well as all pressure terms are constant with respect to time, Equation H-35 may be cast into a differential form with respect to time t:

$$-u_b \frac{d\,u_b}{dt} + g\frac{dz}{dt} = 0\,.$$

Equation H-38

Where, u_b now simply represents the bulk fluid outflow speed.

The quantity of greatest interest is the total mass outflow m_o as a function of time. In order to recast the equation as a differential equation in m_o, the first step is to recognize that the mass release rate dm_o/dt may be expressed in terms of the instantaneous flow velocity, as shown in Equation H-39.

$$\frac{dm_o}{dt} = \rho A_o u_b \;\&\; \frac{du_b}{dt} = \frac{1}{\rho A_o}\frac{d^2 m_o}{dt^2}\,,$$

Equation H-39

with A_o representing the cross-sectional area of the orifice. Once an expression is obtained for dz/dt in terms of differentials of m_o, the equation may be cast into the form of an ordinary differential equation.

Equation H-40 represents the formula for computing the volume of liquid inventory remaining in the tank at time t:

$$V_l(t) = \frac{\pi D^2 z_l(t)}{4} = \frac{m_l(t)}{\rho} \;\&\; \frac{dz_l}{dt} = -\frac{4}{\rho\pi D^2}\frac{dm_l}{dt} = \frac{4}{\rho\pi D^2}\frac{dm_o}{dt}$$

Equation H-40

Where, $V_l(t)$ and $m_l(t)$ represent the volume and mass inventory of liquid remaining inside the tank, respectively, at time t while r and D denote the liquid density and diameter of the tank. Substituting this

$$\frac{1}{\rho A_o^2}\frac{dm_o}{dt}\frac{d^2 m_o}{dt^2} - \frac{4g}{\pi D^2}\frac{dm_o}{dt} = 0\,.$$

Equation H-41

last expression obtains:

Final reconfiguration of this equation yields Equation H-42.

$$\frac{d^2 m_o}{dt^2} = \frac{-4g\rho A_o^2}{\pi D^2}\,.$$

Equation H-42

In order to solve the above second order differential equation, two initial conditions are required. One condition is that at time zero, $m_o(t{=}0) = 0$. The other condition is derived by solving the Bernoulli equation directly for the special case at time zero since $z(t{=}0) = z_i$ representing the initial liquid level

$$\left.\frac{dm_o(t)}{dt}\right|_{t=0} = \rho A_o \sqrt{2\left[g(z_i - z_o) - \frac{\Delta p}{\rho}\right]}$$

Equation H-43

above the outlet centerline axis is given, yielding:

Now that the two initial conditions to the second order linear ordinary differential equation are known, the unique solution is given by Equations H-44 and H-45.

$$\frac{dm_o(t)}{dt} = -\frac{4g\rho A_o^2}{\pi D^2} t + \rho A_o \sqrt{2\left[g(z_i - z_o) - \frac{\Delta p}{\rho}\right]}$$

Equation H-44

$$m_o(t) = -\frac{2g\rho A_o^2}{\pi D^2} t^2 + \rho A_o \sqrt{2\left[g(z_i - z_o) - \frac{\Delta p}{\rho}\right]}\ t$$

Equation H-45

Only times for which $dm_o/dt>0$ are physically relevant, and since dm_o/dt is monotone decreasing we have the duration of the release given by $t=t_{max}$ satisfying

$$\left.\frac{dm_o(t)}{dt}\right|_{t=t_{\max}} = 0\ ,$$

Equation H-46

Solving for t_{max} in the Equation above yields:

$$t_{\max} = \frac{\pi D^2}{4 g A_o} \sqrt{2\left[g(z_i - z_o) - \frac{\Delta p}{\rho}\right]}\ .$$

Equation H-47

H.2.4 OUTFLOW FROM A SPHERICAL TANK

Although a spherical tank is a seemingly benign perturbation away from a simple cylindrical tank, this particular geometry results in a much more complicated expression for the mass flow rate of liquid out of the vessel. The volume of liquid inventory as a function of liquid free surface elevation is given by:

$$V_l(t) = \frac{2}{3}\pi R^3 \int_0^{\alpha} \sin\varphi \, d\varphi + \tfrac{1}{3}\pi d^2 (z - R)$$
$$= \frac{2}{3}\pi R^2 z + \pi z (2R - z)(z - R)$$

Equation H-48

Where,

$$\alpha = \cos^{-1}\left(1 - z/R\right)$$
$$(0 \le \cos^{-1}(x) \le \pi) \; \forall \; x$$

Equation H-49

and *R*, *z*, and *d* represent the tank radius, elevation of the liquid free surface above the bottom of the tank,

$$d = \sqrt{R^2 - (R - z)^2} = \sqrt{z(2R - z)}$$

Equation H-50

and one half the chord length of the liquid free surface, or:

The change in liquid level *z* can be related to the mass outflow rate using the time derivative of Equation H-48:

$$\frac{dV_l(t)}{dt} = -\frac{1}{\rho}\frac{dm_o}{dt} = -\pi\left\{3z^2 - 6Rz + \frac{4}{3}R^2\right\}\frac{dz}{dt}$$

Equation H-51

or equivalently,

$$\frac{dz}{dt} = \left[\pi\rho\left(3z^2 - 6Rz + \frac{4}{3}R^2\right)\right]^{-1}\frac{dm_o(t)}{dt}$$

Equation H-52

$$\frac{1}{\rho A_o^2}\frac{d^2 m_o}{dt^2} - \frac{g}{\pi\left(3z^2 - 6Rz + \frac{4}{3}R^2\right)} = 0.$$

Equation H-53

Finally substituting Equation H-52, yields:

By noting that the mass of outflow at time t is expressed as $m_o = m_{tot} - \mathrm{r}V_l(t)$ where m_{tot} is the total mass of liquid inventory inside the vessel at time t=0 and inspecting the form of the expression for $V_l(t)$ given in Equation H-48, m_o is a cubic polynomial in the variable z and hence a closed-form analytic solution exists for z as a function of m_o.

Therefore, Equation H-53 can be recast into an ordinary differential equation in the one dependent variable, m_o. The resulting equation, however, is complicated, highly nonlinear in m_o, and does not lend itself to a solution without the use of rather involved numerical techniques.

An alternate approach is to compute an average flow rate by simply taking the total mass of liquid that can flow out of the vessel and divide by the time t_{max} required for the liquid level to fall from the initial elevation z_i to the elevation of the discharge orifice, z_o. This time is expressed in Equation H-54.

$$t_{\max} = \frac{\pi}{15 C_o A_o}\sqrt{\frac{2(z_i - z_o)}{g}}\left(5D z_i + 10D z_o - 3z_i^2 - 4 z_i z_o - 8 z_o^2\right)$$

Equation H-54

See Hart and Sommerfeld (1993) for additional details of this derivation.

H.2.5 OUTFLOW FROM PROCESS VESSELS OF OTHER VARIOUS SHAPES

Equations for the drainage time of vessels for other geometrical shapes are presented in Lee and Sommerfeld (1994). This is a starting point for safety analysts in establishing techniques for this type of problem.

H.3 ANALYTICAL METHODS FOR POOL BOILING AND EVAPORATION

In the event of a boiling liquid pool, two simple expressions for obtaining a first-order conservative approximation to the mass evaporation rate are presented:

- Convective boiling; and,
- Conductive boiling.

In addition, various evaporation rate calculations are presented for nitric acid and carbon tetrachloride to emphasize the complexities of accurately assessing evaporation rates.

H.3.1 CONVECTIVE BOILING

Equation H-55 presents a technique to calculate the mass evaporation rate (m_v) due to convective boiling:

$$m_v = k_{air} \frac{A_p}{L_p} Nu_L \frac{(T_{air} - T_b)}{H_v}$$

Equation H-55

Where,

m_v	=	mass evaporation rate (kg/m^2·s);
k_{air}	=	thermal conductivity of air (kJ/m·^{o}K);
A_p	=	pool surface area (m^2);
L_p	=	pool effective diameter in the wind direction (m);
Pr	=	$\mu_{air} c_{p_{air}} / k_{air}$
μ_{air}	=	viscosity of air at ambient temperature (poise);
$c_{p_{air}}$	=	heat capacity of air at constant pressure (kJ/kg·^{o}K);
T_{air}	=	air temperature (^{o}K);
T_b	=	liquid ambient boiling temperature (^{o}K); and,
H_v	=	liquid latent heat of vaporization (kJ/kg).

and,

$$Nu_L = \begin{cases} 0.664\, Pr^{1/3} Re_L^{1/2} & \text{for } Re_L \le 320{,}000 \\ 0.037\, Pr^{1/3} \left(Re_L^{0.8} - 15200\right) & \text{for } Re_L > 320{,}000 \end{cases}$$

Equation H-56

H.3.2 CONDUCTIVE BOILING

Equation H-57presents a technique to calculate the mass evaporation rate (m_v) due to conductive boiling:

$$m_v = \frac{k_s A_p (T_{air} - T_b)}{H_v \sqrt{\pi \varepsilon t}}$$

Equation H-57

Where,

k_s	=	thermal conductivity of ground surface (kJ/m·°K);
A_p	=	pool surface area (m^2);
t	=	time (s);
T_{air}	=	air temperature (°K);
T_b	=	liquid ambient boiling temperature (°K); and,
T_g	=	ground surface temperature (°K);
ε	=	$k_s/(\rho_s c_{p_s})$
ρ_s	=	density of ground surface (kg/m^3);
c_{p_s}	=	heat capacity of ground surface at constant pressure (kJ/kg·°K); and,
H_v	=	liquid latent heat of vaporization (kJ/kg).

Conductive boiling, or conductive heat transfer from the ground, is generally the dominant driving mechanism for boiling in the case of most chemical liquids. However, in the case of some cryogenic releases (e.g., sub-cooled anhydrous ammonia, chlorine), the ground conduction is dramatically reduced if there is moisture present in the substrate since a layer of ice has a thermal conductivity much lower than that of most ground surface substances and it quickly forms at the base of the pool. Furthermore, a thin vapor film frequently forms at the interface between the ground surface and the pool, which further reduces the effective conductivity in that region and limits the amount of heat transfer into the pool. Therefore, Equation H-57 is generally quite conservative during the majority of the boiling regime and most accurately reflects true vaporization conditions at the first instant that the liquid comes into contact with the ground surface. Conversely, Equation H-55 is more representative of the steady-state vaporization of a pool once the ground surface temperature drops below the boiling temperature of the liquid.

H.3.3 NITRIC ACID AND CARBON TETRACHLORIDE POOL EVAPORATION RATES

An alternative correlation that is commonly used in estimating pool evaporation rates and that has been demonstrated to provide lower estimates of pool evaporation rate for a nitric acid and carbon tetrachloride spill is presented. Furthermore, example hand calculations have been provided for the same two releases based on simple models of heat and mass transfer and compared to the experimental correlations to obtain even a less conservative estimate for the pool evaporation rate.

The following calculations employ a relatively simple means of assessing the accuracy of the pool evaporation source term calculations. Illustrative examples are given that assume liquid nitric acid and liquid carbon tetrachloride spill onto the ground surface and form a pool that will be subject to evaporative sub-cooling. The mass evaporation rate is determined by the following factors:

1. Molecular diffusion and mass transport;
2. Conductive heat transfer;

3. Radiative heat transfer;
4. Convective heat transfer;
5. Bulk liquid heat transfer; and,
6. Internal heat content.

The following detailed source term calculations treat provide an upper bound on the potential impact of an evaporating pool in the case that all six evaporation source term factors were considered.

H.3.3.1 NITRIC ACID POOL EVAPORATION

Vapor is entrained by air flowing over the surface of the pool. The rate of mass transfer is expressed in Equation H-58:

$$m_v = -\frac{k_m P_t M_w}{R T_s} \ln\left[1 - \frac{P_v}{P_t}\right]$$

Equation H-58

Where,

k_m	=	mass transfer coefficient (m/s);
P_t	=	sum of atmospheric pressure and partial pressure of chemical vapor (Pa);
M_w	=	molecular weight of chemical (kg/mole);
R	=	ideal gas constant = 8.31424 J/mole·^{o}K;
T_s	=	pool surface temperature (^{o}K);
P_v	=	chemical vapor pressure at temperature T_s (Pa).

Kulmala (1988) and Barrett and Clement (1988) provide detailed derivations of this expression and Studer, Cooper, and Doelp (1988) provide a technique for practical use of this expression in the context of pool evaporation.

Equation H-58 is a specific instance of the mass transfer due to diffusion through a transpired boundary layer. A more general form is presented in Kays and Crawford (1987). While the transpired boundary layer model is not needed for the low vapor pressure associated with HNO_3, CCl_4 evaporates much more rapidly and therefore the transpired boundary layer model is necessary. This will be shown in Section H.3.3.2. It is convenient, then, to operate with the single model for CCl_4 and apply it to HNO_3 as a degenerate case. Mass evaporation equations are part of standard diffusion boundary layer literature and can be found in numerous texts (see Kays and Crawford; Incropera and DeWitt).

The mass transfer coefficient may be related to the Sherwood number (Sh), coefficient of diffusivity of the chemical in air (D_{ba}) and the effective path length of air flowing over the pool, which is usually the effective diameter of the pool (L), as shown in Equation H-59:

$$k_m = Sh \frac{D_{ba}}{L}$$

Equation H-59

The diffusion coefficient may be approximated by a group contribution method attributed to Fuller et al. (Reid et. al., 1987), as shown in Equations H-60 and H-61:

$$D_{ba} = \frac{10^{-3}\ T_a^{1.75}\ M_{w_{ab}}^{1/2}}{P_a\left[\left(\sum v\right)_a^{1/3} + \left(\sum v\right)_b^{1/3}\right]^2}$$

Equation H-60

Where, the sums apply to the atomic diffusion volumes for each component in the chemical molecule and,

$$M_{w_{ab}} = \frac{M_{w_a} + M_{w_b}}{M_{w_a} M_{w_b}}$$

Equation H-61

The subscripts b and a, refer to the chemical species and air, respectively. In particular, M_{w_b} and M_{w_a} denotes the molecular weight of nitric acid and air, respectively.

Assuming the air temperature is 40 degrees C (313.15°K) and M_{w_b}=63.02 g/mole, M_{w_a}=28.97 g/mole, (∑v)a=20.1 and,

$$\begin{aligned}\left(\sum v\right)_b &= v(H) + v(N) + 3v(O)\\ &= 1.98 + 5.69 + 3(5.48)\\ &= 24.11\end{aligned}$$

Equation H-62

$$D_{ba} = 1.64x10^{-6}\ \mathrm{m}^2/\mathrm{s}$$

Equation H-63

and substituting the above values into Equation H-59 and rearranging yields Equation H-64.

$$L_{\max} = \sqrt{\frac{4\,x\,(\mathrm{pool\,area})}{\pi}}$$

Equation H-64

Instead of using the effective length (L), conservatively take L to be the diameter of the pool and assume a pool area of 91 m^2; L_{max} becomes 10.8 m.

The Sherwood number may be expressed as in Equation H-65:

$$Sh = 0.037\left(Re_L^{0.8} - 15200\right)Sc^{1/3}$$

Equation H-65

Where, the Schmidt number (Sc), and the Reynolds number (Re_L) are expressed in Equations H-66 and H-67:

$$Sc = \frac{\mu_v}{\rho_v\ D_{ba}}$$

Equation H-66

$$Re_L = \frac{\rho_\infty u_\infty L}{\mu_\infty}$$

Equation H-67

With,

ρ_∞ = main stream density (kg/m^3);

u_∞ = main stream ambient wind speed (m/s); and,

μ_∞ = main stream viscosity (poise).

The Schmidt number arises when considering a laminar boundary layer on a flat plate in which the diffusion was occurring as a result of some mass-transfer condition at the surface. The concentration and velocity profiles will have the same shape when the dynamic viscosity $\nu_\infty = \mu_\infty/\rho_\infty$ satisfies $\nu_\infty = D_{ba}$ or $\nu_\infty/D_{ba}=1$.

Note: The above correlation for the Sherwood number only holds true for Re>15,200. Furthermore, the mixed boundary layer, the Sherwood number correlation is not valid for Sc<0.6 (see Incropera and DeWitt). Although the above expression for the Sherwood number is commonly quoted in analyses studying the evaporation of liquids, the particular expression was derived from studying the heat transfer coefficient of a dry body. Therefore an alternative, and presumably more appropriate, expression for the Sherwood number in the event of a liquid spill is presented in Equation H-68.

The Schmidt and Reynolds numbers are many times calculated with the fluid properties at infinity in boundary layer coordinates rather than vapor properties (see Incropera and DeWitt). Occasionally one will find the fluid properties calculated at the average of the infinity and wall values. Using the outer fluid properties will significantly affect the resultant value for the Sherwood number in the case of cryogenic spills, for instance, where the thermodynamic properties are sensitive to small changes in ambient conditions. The work of Smolsky and Sergeyev in the area of heat and mass transfer from free surfaces of liquids into a heated turbulent stream offers the following alternate empirical technique shown in Equation H-68:

$$Sh = 0.094\, Re^{0.8}\, Sc^{0.33}\, Gu^{0.2},$$

Equation H-68

Where,

$$Gu = \frac{T_\infty - T_w}{T_\infty}.$$

Equation H-69

Gu denotes the Guhmann number with T_∞ and T_w denoting the mainstream and liquid surface temperature, respectively.

This expression is based on experimental studies of the heat and mass transfer from the free surfaces of various liquids into a heated turbulent air stream. Equation H-69 is therefore recommended as the more appropriate estimate of the Sherwood number in the case of an evaporating pool. It is recognized, however, that estimates of the Guhmann number are vulnerable to high degrees of uncertainty. In an effort to circumvent this issue, the Sherwood number should be estimated using Equation H-69 with the

dynamic viscosity evaluated as the average of the main steam (i.e., air) and boundary layer vapor (i.e., chemical) dynamic viscosities in the definitions of the Schmidt and Reynolds numbers, as depicted in Equations H-70 through H-72:

$$\overline{Re_L} = \frac{u_\infty L}{\bar{\nu}}$$

Equation H-70

$$\overline{Sc} = \frac{\bar{\nu}}{D_{ab}}$$

Equation H-71

$$\bar{\nu} = \tfrac{1}{2}\left(\nu_{air} + \nu_{vapor}\right)$$

Equation H-72

Applying a nitric acid vapor density of 2.18 kg/m^3, u_∞=5 m/s and, due to limited data on HNO_3, approximating the vapor viscosity by the gas viscosity for nitrous oxide at the pool surface temperature of 20°C given to be 1.46E-2 c_p or 1.46E-5 kg/m·s yields v_{vapor}=6.7E-6 m^2/s. The outer fluid properties make use of v_{air}=1.72E-5 m^2/s, for air at 313°K and atmospheric pressure, and the pool diameter length scale L_{max} = 10.8 m, the averaged Schmidt and Reynolds numbers are recalculated as shown in Equation H-73.

$$\bar{\nu} = 1.19x10^{-5}$$
$$\overline{Sc} = 7.29$$
$$\overline{Re_L} = 4.52x10^{6}$$

Equation H-73

Finally, substituting all the above intermediate results into Equation H-68 obtains a Sherwood number from Equation H-74.

$$Sh = 1.4x10^{4}$$

Equation H-74

The mass transfer coefficient therefore becomes the following from Equation H-75.

$$k_m = 2.13x10^{-3}\ \mathrm{m/s}$$

Equation H-75

Therefore, the mass transfer rate is estimated to be the following value as calculated from Equation H-76:

$$m_{tran} = \frac{-(2.11x10^{-3}\ \mathrm{m/s})(101325\ \mathrm{Pa} + 413.2\ \mathrm{Pa})(0.06302\ \mathrm{kg/mole})}{(8.314\ \mathrm{J/mole \cdot K})(293.15\ \mathrm{K})} \ln\left[1 - \frac{413.2\ \mathrm{Pa}}{101325\ \mathrm{Pa}}\right]$$
$$= 2.29\ \mathrm{x}10^{-5}\mathrm{kg/m^2 \cdot s}$$
$$= 0.0229\ \mathrm{g/m^2 \cdot s}$$

Equation H-76

The total mass transfer rate is simply the product of m_{tran} and the pool area of 91 m^2, as shown in Equation H-77:

$$m_v(\mathrm{HNO_3}) = 2.08 \ \mathrm{g/s}$$

Equation H-77

H.3.3.2 CARBON TETRACHLORIDE POOL EVAPORATION

Equation H-78 is used to estimate the diffusion coefficient by means of the group contribution method detailed above.

M_{w_b}=153.83 g/mole, M_{w_a}=28.9 g/mole, $(\Sigma v)_a$=20.1 and

$$\begin{aligned}(\Sigma v)_b &= v(C) + 4v(Cl) \\ &= 16.5 + 4(19.5) \\ &= 94.5\end{aligned}$$

Equation H-78

Substituting the above values yields Equation H-79.

$$D_{ba} = 8.93x10^{-6} \ \mathrm{m/s}$$

Equation H-79

Assuming a pool area of 73 m^2, the length scale L_{max} becomes 9.64 m. Assuming a CCl_4 vapor density of 5.32 kg/m^3, u_∞=5 m/s, and the vapor viscosity at the pool surface temperature of 20°C determined to be 9.66E-3 c_p or 9.66E-6 kg/m·s yields v_{vapor}=1.82E-6 m^2/s.

The outer fluid properties, v_{air}=1.72E-5 m^2/s for air at 313°K and atmospheric pressure, the averaged fluid properties Schmidt and Reynolds numbers are calculated to be what is shown in Equations H-80 through H-82.

$$\begin{aligned}\bar{v} &= 9.51x10^{-6} \\ \overline{Sc} &= 1.06 \\ \overline{Re}_L &= 5.07x10^{6}\end{aligned}$$

Equation H-80

Substituting all the above intermediate results into Equation G-31 obtains:

$$Sh = 8.15x10^{3}$$

Equation H-81

The mass transfer coefficient therefore becomes:

$$k_m = 7.55x10^{-3} \ \mathrm{m/s}$$

Equation H-82

Therefore, the mass transfer rate is estimated to be what is shown in H-83.

$$m_{tran} = \frac{-(7.5x10^{-3}\ \text{m/s})(101325\ \text{Pa} + 2\text{x}10^{4}\ \text{Pa})(0.15383\ \text{kg/mole})}{(8.314\ \text{J/mole}\cdot\text{K})(293.15\ \text{K})} \ln\left[1 - \frac{2\text{x}10^{4}\ \text{Pa}}{101325\ \text{Pa}}\right]$$
$$= 1.27\text{x}10^{-2}\ \text{kg/m}^2\cdot\text{s}$$
$$= 12.7\text{g/m}^2\cdot\text{s}$$

Equation H-83

Using a pool area of 73 m^2, the total mass transfer rate is simply the product of m_{tran} and the pool area, as shown in Equation H-84:

$$m_v(\text{CCl}_4) = 0.928\ \text{kg/s}$$

Equation H-84

In contrast to nitric acid, the boiling temperature of CCl_4 is closer to that of ambient temperature and the effects of bulk liquid heat transfer and internal heat content play a more important role in the overall mass evaporation rate. Both of these factors serve to mitigate the release rate to some extent. However, because of the greater volatility of CCl_4, solar radiation and convective heat transfer have a significant effect in terms of increasing overall mass evaporation rate.

No simple correlation has the capabilities of accurately incorporating all the various thermal phenomena taking place in the event of a volatile liquid release. However, a simple correlation can provide a reasonable conservative estimate of the true evaporation rate.

Compare the evaporation correlation used in the CEI guidelines (TNO, 1979), as shown in Equation H-85.:

$$\dot{m} = 9\text{x}10^{-4} A_p^{0.95} \frac{(MW)\,P_v}{T + 273}$$

Equation H-85

Where,

$\dot{m}$	=	pool evaporation rate (kg/hr);
A_p	=	pool area (m^2);
MW	=	chemical molecular weight (g/mole);
P_v	=	vapor pressure of the chemical at the characteristic temperature (kPa); and,
T	=	characteristic pool temperature (^oC).

with a similar closed-form expression described by Clewell (1983), as shown in Equation H-86:

$$\dot{m} = 8x10^{-2} u^{3/4} A_p Z \left(1 + 4.3x10^{-3} T^2\right)$$

Equation H-86

Where, Z is the volatility factor of species x with respect to hydrazine expressed as such in Equation H-87.

$$Z = \frac{(MW)_x \; P_{v_x}}{(MW)_{hydrazine} P_{v_{hydrazine}}}$$

Equation H-87

Predicted evaporation rates for nitric acid and carbon tetrachloride at various ambient temperatures with a fixed pool surface area of 1 meter^2 and an ambient wind speed of 5 m/s are provided in Figure H-1 and Figure H-2, respectively.

In the turbulent boundary layer, the mass transfer coefficient is proportional to $u^{0.8}$ and $L^{1.8}$, while in the TNO correlation, the mass transfer coefficient is proportional to $u^{0.8}$ and $L^{1.9}$. Accordingly, the TNO expression will be become progressively more conservative as the pool area increases and as the laminar region (i.e., where Sh is proportional to $Re^{1/2}$) increases.

As for the additional modes of heat transfer, evaporative cooling offsets heating effects due to ground conduction and solar radiation. For volatile liquids such as CCl_4, Clewell suggests a pool temperature decrease of 10-20°C is not unreasonable due to evaporative cooling (Long, 1994). By setting the pool temperature equal to the air temperature, a conservative evaporation rate is maintained. This is equivalent to assuming a very large convective heat transfer coefficient between the pool and the air.

The standard turbulent boundary layer calculation also suffers from lack of data as the diffusion coefficients for CCl_4 vapor is calculated based on the chlorine diffusion volume which, according to Perry (Reference), is based on very little data. No data was found to directly compare to the calculated diffusion coefficients for HNO_3 as well.

Table H-2 compares the results for the hand calculations, the TNO model, and the Clewell model in the case of the nitric acid and carbon tetrachloride evaporation rates. Although there is relatively good comparison among all three models in the case of nitric acid, there is a disparity among results in the case of carbon tetrachloride. The hand calculation is in itself conservative, but even after allowing for pool cooling and other mitigating features, the question as to whether simple correlations can be relied upon to yield conservative results for a wide class of chemicals remains unanswered.

These examples were chosen to dramatize the point that one should never blindly place faith in experimental correlations based on limited data.

Table H-2. Comparison of Results for Three Evaporation Models as Applied to HNO_3 and CCl_4.

Model	HNO_3 Evaporation Rate (g/sec)	CCl_4 Evaporation Rate (g/sec)
Hand Calculation	**2.08**	**928**
TNO	**1.53**	**342**
Clewell	**2.82**	**606**

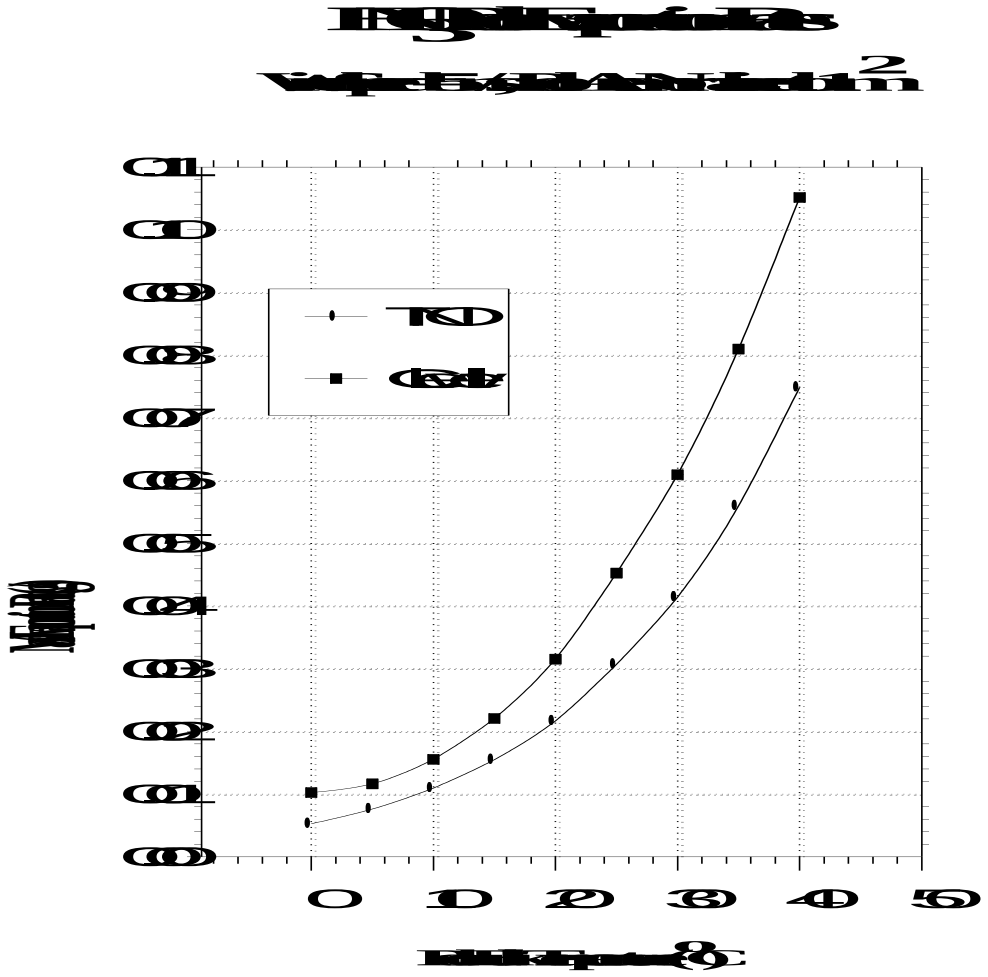

Figure H-1. Comparison of Evaporation Rate Predictions for 60 percent Solution of Nitric Acid with a 1 m^2 Surface Area.

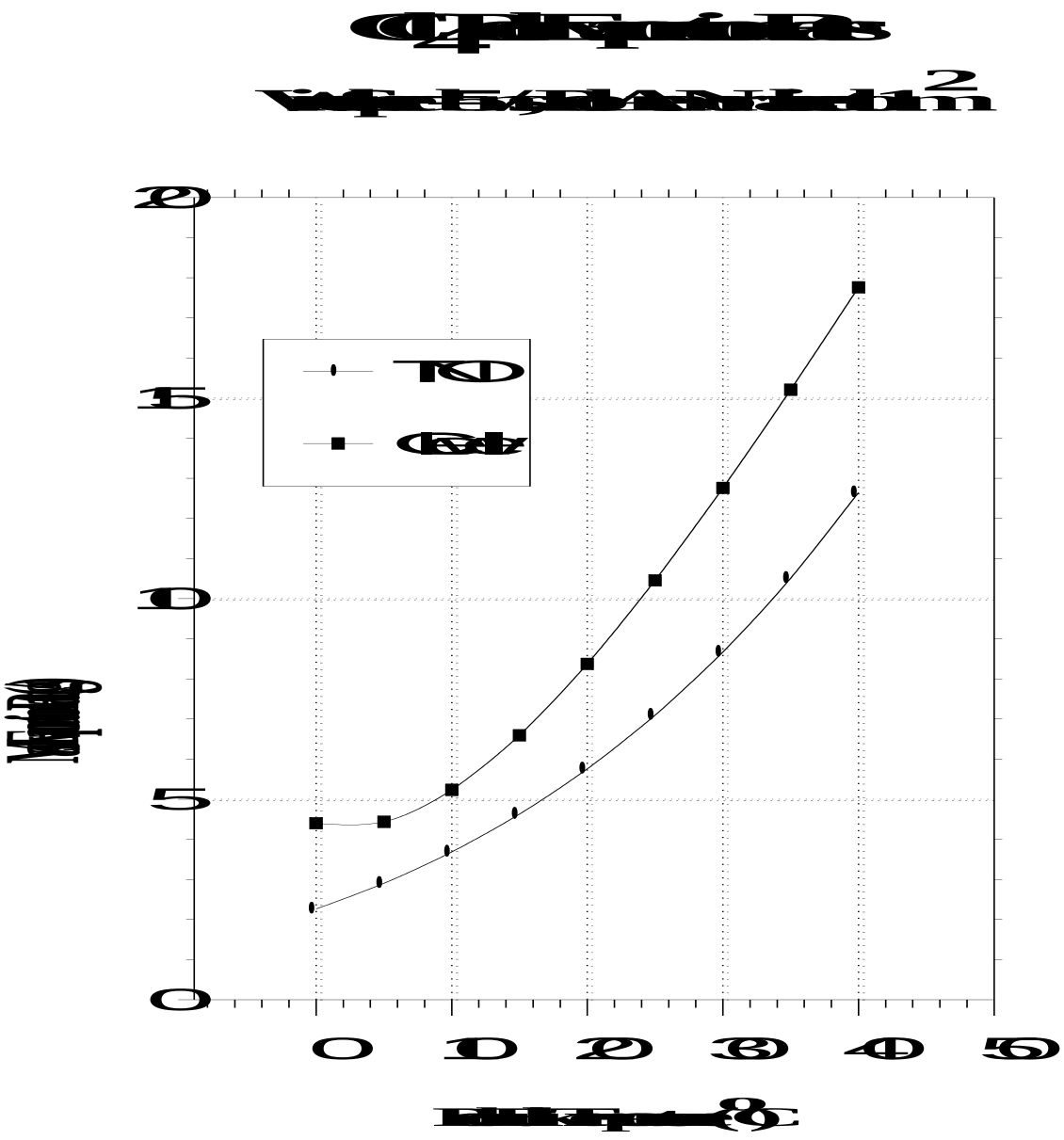

Figure H-2. Comparison of Evaporation Rate Predictions for Carbon Tetrachloride with a 1 m^2 Surface Area.

APPENDIX I CRITICALITY ACCIDENTS

I.1 INTRODUCTION

The purpose of this appendix is to provide guidance for the quantitative estimate of radiological doses to support the qualitative assignments of consequences for the DSA hazard evaluation as discussed in Section 2.4.5, Nuclear Criticality Hazard Evaluation, of this handbook. The general approach to evaluate a dose from a criticality accident is:

1. Determine the fission yield (i.e., power history).
2. Determine the direct dose at the appropriate distance.
3. Determine fission product quantities.
4. Determine the source term for inhalation dose. This includes the determination of nuclides present in the released cloud at the time of exposure, including the effects of decay during transport.
5. Determine external beta and gamma doses (i.e. cloud shine).

Guidance for these steps is provided in this appendix.

Criticality accident hazards are unique to nuclear facilities and even then only to a subset of these facilities. This subset has a fissile material inventory that is significant, generally defined as exceeding the single parameter subcritical mass limits given in ANSI/ANS-8.1-2014, *American National Standard for Administrative Practices for Nuclear Criticality Safety in Operations with Fissionable Materials Outside Reactors*, and requiring specific criticality controls to reduce the likelihood of a criticality accident to an acceptable level. This acceptable level is generally one that results in the accident likelihood being judged to be incredible, at least for individual processes. For facilities requiring such process-specific criticality controls, the hazard categorization based on the criticality accident hazard would generally be Hazard Category (HC) 2, in accordance with DOE-STD-1027, Change Notice 1, *Hazard Categorization and Accident Analysis Techniques for Compliance with DOE Order 5480.23, Nuclear Safety Analysis Reports*.. This is technically excessive, but currently prescribed by the Code of Federal Regulations.

If either “segmentation” or “nature of process” arguments and analyses can lead to the conclusion that a criticality accident is incredible, even for total fissile inventories that exceed the ANS-8.1 subcritical mass limits, then a facility’s hazard categorization would not be influenced by criticality accident considerations.

Commonly accepted terminology, as used in the criticality safety discipline, is found in report LA-11627-MS, *Glossary of Nuclear Criticality Safety Terms* (Paxton, 1989). In particular the following two terms are important to the discussions in this Appendix:

> **Criticality Accident:** The release of energy as a result of accidentally producing a self-sustaining or divergent fission chain reaction.
>
> **Criticality Safety:** Protection from the consequences of a criticality accident, preferably by prevention of the accident. Encompasses procedures, training, and other precautions in addition to physical protection.

Criticality accidents outside of reactors, i.e., process facility criticality accidents, are the subject of this Appendix. Criticality accidents associated with reactors are considered and analyzed under the umbrella of Reactor Safety, a separate discipline.

Process facility criticality accidents have been few, both in the US and worldwide, 7 and 22, respectively; and fatalities have been similarly infrequent, 2 and 9, respectively (LA-13638, McLaughlin, et. al., 2000). In almost all of these accidents the survivors suffered no long-term effects from the radiation exposures. The most recent US criticality accident was in 1978 and worldwide in 1999. No accidents have resulted in any significant mechanical energy release, and radiation exposure is the only significant hazard. From criticality accidents seen to date, significant doses have only been associated with nearby workers, with insignificant exposures to co-located workers outside the facility, the public, or the environment.

When criticality accident likelihoods are judged to be non-trivial in a facility, then it is almost always concluded that a criticality accident alarm system is an appropriate safety system in accordance with ANSI/ANS-8.3, *Criticality Accident Alarm System*. Competing risks associated with the response to false alarms may, rarely, modify the decision as to when a criticality accident alarm should be installed.

I.2 REGULATORY REQUIREMENTS, RECOMMENDATIONS AND GUIDANCE

DOE Order 420.1C, *Facility Safety*, and 10 CFR 830 Subpart B, *Safety Basis Requirements*, both include words reflecting the process analysis requirement from ANSI/ANS-8.1 § 4.1.2, Process Analysis:

> *"Before a new operation with fissionable material is begun, or before an existing operation is changed, it shall be determined that the entire process will be subcritical under both normal and credible abnormal conditions."*

Credible accidents, including credible criticality accidents, are analyzed in the Documented Safety Analysis (DSA). It is assumed that controls for the prevention of criticality accidents are, or will be, in place. It is also assumed that the need for criticality alarms will be determined, and alarms installed, if justified. This Appendix also assumes that enough fissionable material is being handled in a manner such that any potential criticality accident is identified by the hazards evaluation. If the fissionable quantities are below the minimum subcritical limits in the appropriate ANS standard (ANSI/ANS-8.1-2014 or 8.15-2014) analysis of a criticality accident may not be needed, and in this instance would not be identified in the hazard evaluation.

I.2.1 UNMITIGATED ANALYSIS

DOE-STD-3009 provides guidance on unmitigated accident analysis. In essence, unmitigated analysis means that controls intended to prevent or mitigate an accident are assumed not to function. In the case of a criticality accident, this means, in part, that the accident is assumed to happen with no mitigative features taken into account. An exception to this is that passive safety features that can be shown to survive the initiating event may be considered in the analysis. For example, if a seismic event causes a criticality accident in a shielded area (including building walls), and the shield can be shown to survive the event, then the effectiveness of the shield in mitigating worker accident doses can be accounted for in the unmitigated analysis. For the analysis of criticality accidents that have the potential for lasting longer than an initial pulse, the accident duration should be limited to two (2) hours, except for scenarios that are slow to develop and complete. In those cases, the accident duration should be limited to eight (8) hours (based on guidance from DOE-STD 3009). These analyses should be based on bounding scenarios. The

dose integration time should be based on the specific power history of the accident, limited as discussed above.

DOE-STD-3009[77] requires the analysis of unmitigated accidents to determine the safety classification of needed controls, that is, safety class or safety significant. For purposes of this Appendix, the need for safety class controls is based on the unmitigated consequences to the public at the site boundary, and the need for safety significant controls is based on the unmitigated consequences to the co-located worker. The co-located worker is 100 meters from the criticality accident for direct exposure calculations. For atmospheric dispersion, the co-located worker is 100 m from the building emission point (which is likely different than the direct exposure point). DOE-STD-3009 also has requirements related to selecting safety significant controls based on other criteria; however, these criteria are not addressed in this appendix. In general terms, if the dose to the public at the site boundary is less than 0.05 Sv (5 rem), safety class controls are not needed, and if the unmitigated dose exceeds 0.25 Sv (25 rem) then safety class controls are required. If the dose to the co-located worker at 100 meters is less than 1 Sv (100 rem), safety significant controls are not needed.

For the criticality accident analysis, DOE-HDBK-3010-94 Change Notice 1, *Airborne Release Fractions/Rates and Respirable Fractions for Nonreactor Nuclear Facilities*, provides estimates of fission yields, and is a recognized source for other accident analysis parameters. In addition, ANSI/ANS-8.23-2007, R2012, *Nuclear Criticality Accident Emergency Planning and Response*, requires evaluation of bounding, operational-specific accidents, including locations, yields, and dose determinations. As with any accident parameter, fission yields should be justified and shown to be applicable to the accident situation.

The unmitigated construct requires some assumptions that by their nature limit the magnitude of a criticality accident, thus initiating circular logic. To deal with this issue, guidance for estimating the bounding number of fissions in criticality accidents is provided in section I.3, below. This guidance is based on evolving understanding of the consequences of potential criticality accidents since DOE-HDBK-3010-94 was issued. Application of the DOE-HDBK-3010-94 methods and guidance is judged to provide a more conservative estimate, and may be useful as a scoping calculation to demonstrate that the total doses (direct plus committed) at the site boundary or at 100 m are not significant, in which case further evaluation would not be necessary.

For both existing and new facilities the (preliminary) DSA should provide information as to planned operations and facility layouts and features such as wall compositions and thicknesses. This information should be used with the techniques discussed in Section I.3 to estimate bounding, unmitigated fission yields.

I.3 ACCIDENT FISSION YIELDS

As with many known hazards, the understanding of, and thus the control of, the criticality accident hazard has improved dramatically since this hazard was first introduced in the 1940s with the advent of the production of significant quantities of plutonium and enriched uranium. Both the causes, largely human factors, and the personnel effects, localized to within a few to several meters of the accident location, are now well understood. Nevertheless, risks will never vanish and due diligence should always be applied.

[77] When used without a 2-digit or 4-digit year number after "DOE-STD-3009", it refers to both the 1994 Change Notice 3 and 2014 versions of the DOE Standard. Otherwise, specific versions are referenced.

I.3.1 FISSION YIELDS OF SOLUTION AND SOLUTION-LIKE SYSTEMS

History has shown that process criticality accidents have occurred almost exclusively in (hydrogenous) liquid media. The most common medium was fissile material in nitric acid, followed by an organic solution and then suspensions/slurries. The hydrogenous nature of the medium results in relatively slow fission excursions and insignificant likelihoods of mechanical (destructive) energy releases. The liquid nature of the medium results in a combination of instantaneous bubble generation and thermal expansion as the major feedback mechanisms for limiting the first-spike yield (fissions) of the excursion.

ANSI/ANS-8.23-2007, R2012, Appendix C, provides a comprehensive summary of data from criticality accident simulations in controlled environments and its application to estimating accident yields, both the first spike and the steady-state fission rate should the accident not self-terminate. The data cover broad ranges of key parameters, most importantly the solution volume and the reactivity insertion rate.

Two figures from reference documents, reproduced in ANS-8.23, Appendix C, are also reproduced here. Figure I-1 shows the variation in the specific yield of the first spike for prompt critical excursions from the literature data. As is shown, for all but very rapid excursions the specific fission yield is ~1×10^{15} fissions/liter.

Some of the process criticality accidents did not even reach the prompt critical state and thus had much smaller specific yields. However, this value of ~1×10^{15}/liter is judged to be a practical upper bound for a first spike yield for the purpose of accident analysis. None of the process accidents exhibited specific yields statistically greater than this value. The data in the figure for the very short period excursions, <10 ms, that do show larger specific yields resulted from reactivity insertion rates that are likely not credible during process accident conditions.

Figure I-2 shows a curve judged to be a practical bounding envelope of the integrated specific fissions during the first 10 minutes subsequent to a prompt critical excursion that is neither self-terminating nor otherwise terminated. Application of the information in Figures I-1 and I-2 enables a realistic upper estimate to be made of both the first-spike dose and the integrated dose to workers during evacuation from a postulated process accident. It also enables the analyst to estimate the dose rate at various locations in order to make decisions as to immediate evacuation zone boundaries and appropriate muster locations. Finally, if this 10-minute time window is consistent with site emergency plans and procedures, then the fission yield curve in Figure I-2 would be appropriate for determining bounding co-located worker and public exposures prior to possible further personnel relocations/evacuations.

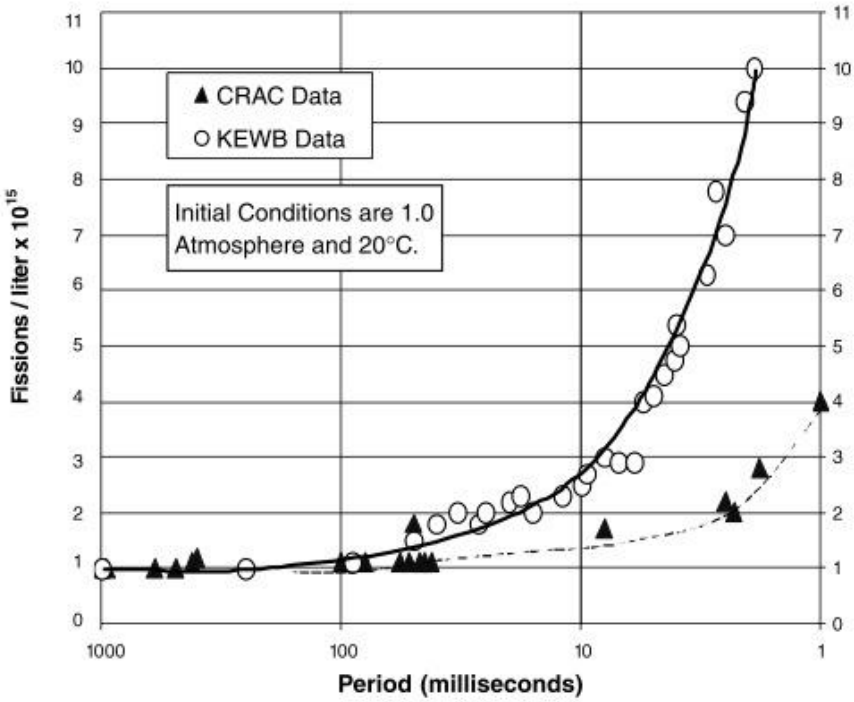

Figure I-1 – Specific fissions in first spike as a function of reactor period

Reactor period is the time required for power to increase by Euler's number (Napier's constant). (reproduced from Figure C.1 of ANSI/ANS 8.23-2007;R2012)

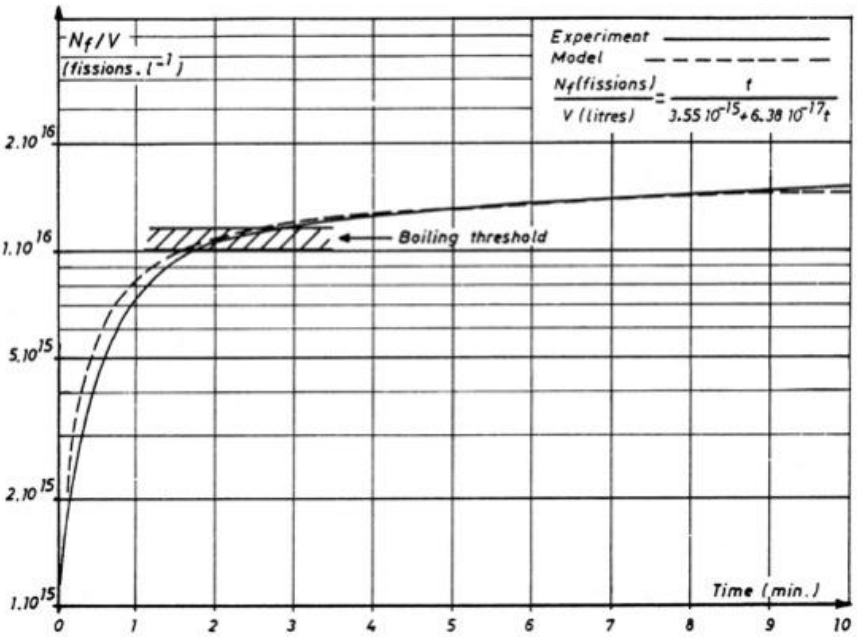

Figure I-2 – Maximum specific fission yield resulting from criticality solution excursions in CRAC and Silene

(reproduced from Figure C.2 ANSI/ANS 8.23-2007;R2012)

For an unmitigated accident with an 8-hour duration there is scant data upon which to base total fission/liter estimates. The Hanford (1961), Novosibirsk (1997) and Tokai-Mura (1999) accidents are the only reported process accidents to have continued fissioning for at least 8 hours. No accident simulations, such as the CRAC series, were allowed to run for more than minutes. Based on these two accidents and the reality that the fission rate is (theoretically) expected to decrease over time, and did in these three accidents, one can only estimate the ratio of the 8-hour fissions to first-spike fissions as perhaps a factor of 30.

The information contained in Figure I-2 has also been incorporated into the Nuclear Criticality Slide Rule that may also be used to estimate bounding fission yields (NUREG/CR-6504). Similar results will be attained.

I.3.2 FISSION YIELDS OF NON-SOLUTION-LIKE SYSTEMS

As the world-wide accident history shows, non-solution accidents are rare. In fact, if one reviews the circumstances leading up to the one reported non-solution accident, it is apparent that this accident was enabled by a working environment that condoned significant procedural violations in the interest of expediency. It is judged that this working environment would be rarely present to a similar extent in nuclear operations today, particularly in the U.S.

Thus, while criticality accidents in non-solution environments, be they metals or compounds/powders or storage operations, will never be 100% risk-free, credible accident scenarios should be readily foreseen and prevented by design. Such events may then be able to be shown be not credible per ANS-8.1 and DOE-STD-3007-2007, *Guidelines for Preparing Criticality Safety Evaluations at Department of Energy Nonreactor Nuclear Facilities*.

I.3.2.1 METALS/SOLIDS

For an unspecified criticality accident with uranium or plutonium in metal form and with no significant moderation, bounding first-spike yields consistent with known accidents, both process and critical experiment, are 1 $x10^{18}$ and 1 $x10^{16}$ fissions, respectively. For these large first-spike yields prompt shutdown due to mechanical shock would be expected. For lesser first-spike yields a delayed-critical fission reaction is bounding and judged to produce maximum 8-hour yields of 1 $x10^{19}$ and 1 $x10^{18}$ fissions respectively. Radiation exposures from metal accidents are known to be essentially all from direct neutrons and gamma rays with insignificant fission product releases. For fissile material operations conducted inside typical facilities with thick concrete walls there would be minimal exposures to co-located workers or the MOI from these bounding fission sources.

I.3.2.2 MODERATED SOLIDS, DRY SOLIDS, AND LARGE ARRAYS

These types of criticality accidents, although discussed in DOE-HDBK-3010-94, are now considered so unlikely that they need not be further evaluated for the DSA hazard evaluation if determined to be not credible per the NCS analysis. Accident recovery operations, e.g., from a significant seismic event or fire, may warrant consideration of scenarios such as flooded fissile metal pieces or powders, but this is not a process operation, it cannot be accurately defined, and it is appropriately handled during the accident recovery process.

I.3.3 FISSION YIELDS OF AUTOCATALYTIC ACCIDENTS

This deals with a criticality accident where the reactivity initially increases as the fission reaction progresses, generally due to the effects of temperature and pressure causing material rearrangement within the fissioning medium. One early estimate of excursion yields in a specific facility postulated an unusual accident whose reactivity initially increased due to the initial energy release (Woodcock, 1965). This type of event has not been observed in accident history. However, if the accident being evaluated has the potential for self-propagation, this should be considered.

I.4 EVALUATION OF DIRECT RADIATION DOSE

The prompt dose depends only upon the number of fissions in the criticality accident, the distance from the accident site to the receptor, and the amount of intervening shielding material, such as self-attenuation within the fissioning medium or building walls. The Nuclear Criticality Slide Rule gives curves of unshielded dose as a function of distance, number of fissions, and time after the criticality accident. There is also information on the shielding effect of typical construction materials. This is preferred over the withdrawn NRC Regulatory Guides that have been historically used for DSA development as discussed in Section 6.2.2.2.4, Prompt (Direct) Dose.

I.5 CRITICALITY ACCIDENT SOURCE TERMS

Chapter 5, Source Term Analysis, covers source term estimation in detail depending on the accident stress on the material. For criticality accidents, however, the source term is fundamentally defined by the number of fissions occurring. This specialized subject will therefore be covered as part of this appendix.

There are two main contributors to the criticality accident source term: fission products generated by the excursion, and releases from the fissionable/fissile material itself. Of the criticality accident fission products themselves, the major components of concern have historically been the noble gases (isotopes of krypton and xenon) and radioiodine, due to their propensity to become airborne and escape filtration. It is important, however, to account for the decay products of isotopes, not merely to presume exposure to the radioisotopes initially released.

I.5.1 FISSION PRODUCT INVENTORIES

A criticality accident generates the same types of fission products contained in spent nuclear reactor fuel. These are the primary fission product isotopes along with the subsequent decay of the initial fission products into other radioactive isotopes that, in turn, continue the decay chain. The typical pattern for total fission product activity in a criticality accident is a decrease in activity by orders of magnitude in the first 30 seconds after the criticality accident terminates. This is due to the loss of high-energy, short half-life isotopes that decay almost immediately. The activity then continues to decrease at a slower rate, with the contributions from various elements and classes of elements changing due to the ongoing decay process. Figure I-3 provides an example of this. It depicts total activity and the activity due to noble gases, halogens (of which iodine is one), and solids over time from a criticality accident pulse of 1×10^{18} fissions.

The NRC, in withdrawn Regulatory Guides 3.33, 3.34 and 3.35, provided an estimate of “the radioactivity of significant nuclides released” for fuel reprocessing solutions, uranium solutions, and plutonium

solutions. The criticality accident assumed had a 1 x 10^{18} fissions initial burst followed by 47 bursts of 1.9 x 10^{17} fissions each over the next 8 hours for a cumulative total of 1 x 10^{19} fissions. It is noted that this particular scenario has not been justified in any technical document. The significant nuclides noted were isotopes of krypton, xenon, and iodine. Their activity levels were based on the cumulative yield for the fission energy spectrum, an assumption noted as "very conservative" since it did not consider decay schemes for these nuclides.

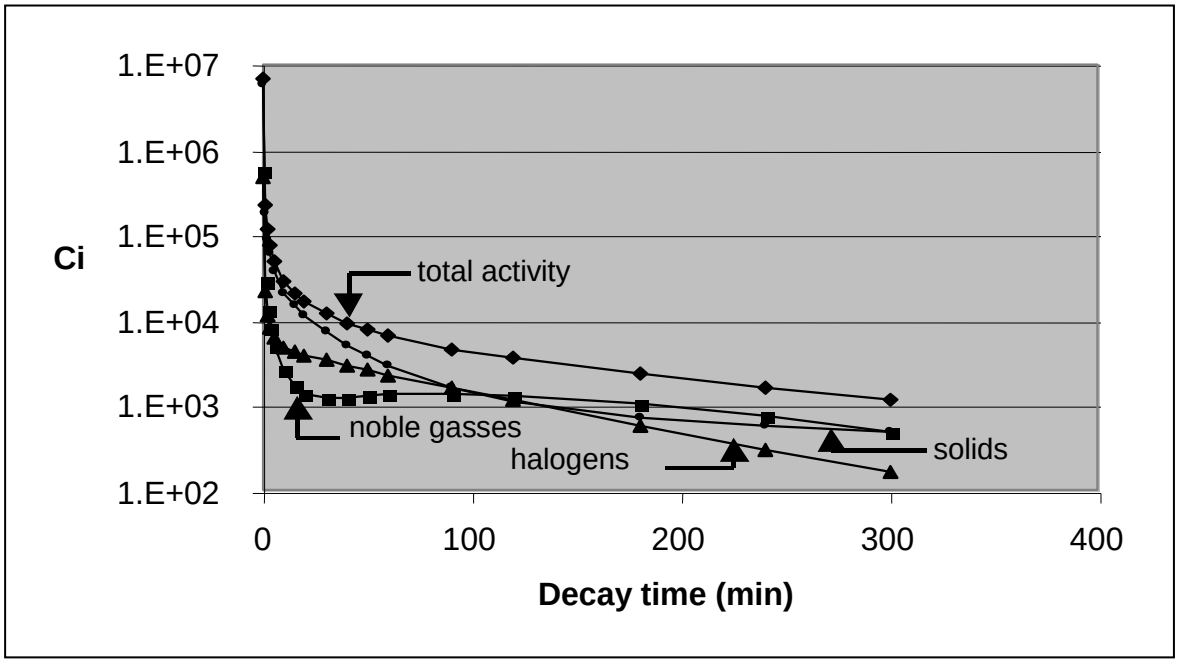

Figure I-3: Fission Product Activity as a Function of Decay Time Following a Criticality Accident Pulse

Historical practice for DOE DSAs has been to use the information in Regulatory Guides 3.33, 3.34, and 3.35 for all criticality accidents, simply scaling the results to reflect total fission yields less than 1 x 10^{19} fissions (and eliminating the 8-hr duration for single spike criticality accidents). However, the Regulatory Guides have been withdrawn. With the availability of modern code systems and cross sections, it is entirely feasible to calculate the fission products from a postulated criticality event.

I.5.2 PARTICULATE RELEASE AND HEALTH RELATED PARAMETERS

As presented in Chapter 5, the Airborne Release Fraction (ARF) and Respirable Fraction (RF) are major parameters in determining the amount of radioactive or other hazardous material released in an accident. These parameters are normally evaluated by comparing a given phenomenology to available experimental data. Unfortunately, no direct criticality accident release experiments have ever been conducted. Further, the fission yields assigned are intended to bound fission product formation as opposed to realistically estimating the physical changes experienced by the fissionable/fissile material. Accordingly, criticality accident release fractions have been developed only in a general sense without attempting to extrapolate them back to detailed phenomenological modeling. The majority of the effort expended in developing them has also focused on the fission product release. However, as related to release of particulates due to

melting of metal, boiling of a solution, heating of powders, or energetic dispersal of a powder, the recommended ARFs and RFs are based on experimental data for those types of changes in the materials.

As presented in Chapter 6, Section 6.2, Radiological Consequence Assessment, the dose a person might receive from the fission products released by a criticality accident depends on many factors. These are discussed in ICRP-68, *Dose Coefficients for Intakes of Radionuclides by Workers*.

Release estimates for solution criticality accidents derive from NRC Regulatory Guides 3.33, 3.34, and 3.35. In these guides, the NRC established three assumptions. First, all noble gases are assumed to be released from solution and subsequently leave the facility. Second, it assumed that 25 percent of radioiodine ultimately escapes from the facility, either because only that much escapes from solution or because only that much of this element does not react with physical surfaces within the facility. Third, it was generically assumed that the criticality accident terminates when 25 percent of the available solution evaporates. The bounding ARF for boiling liquid is 2×10^{-3} (see Chapter 5). Applying the 25 percent factor to this ARF yields an effective release fraction of 5×10^{-4}, which the NRC originally applied to the base matrix of fissile plutonium in solution in Regulatory Guide 3.35.

The values cited above have been reiterated in NUREG/CR-6410, which also formally extended the 5×10^{-4} release fraction to the seven significant isotopes (Sr-91, Sr-92, Ru-106, Cs-137, Ba-139, Ba-140, and Ce-143). That document further noted that the 5×10^{-4} value is considered "applicable to all non-volatile compounds in the liquid." The portion of the actinides released is assumed to be proportional to the mass of actinides in the solution as the actinides are released through the spray caused by the bursting bubbles that reach the surface of the solution. The mass of the actinides depends upon their concentration in the solution.

I.6 CRITICALITY ACCIDENT EXAMPLE

This example is based on the assumption that the selected accident is the "bounding" hypothetical accident after a thorough review of all fissile operations in the facility. Generally, the bounding accident would involve the largest volume in a hydrogenous, liquid environment coupled with making the conservative assumption that the system reaches the prompt critical state such that the information in Figure I-1 would be applicable. This would lead to the largest number of fissions and thus be "bounding." Rare, extenuating circumstances such as larger accidents that are more remote or in shielded areas may result in a "bounding" accident that does not coincide with the largest number of fissions.

This example assumes that there is a fissile solution that inadvertently and very rapidly accumulates in a 150-liter vessel/volume and that the system just reaches the prompt critical state as the vessel becomes full. Thus, conservatively assuming that the prompt critical state is reached and that the system remains critical, and then applying the information from Figure I-2, we can calculate the first spike, 10-minute, and 8-hour fissions as:

First spike yield = 150 liters x 1×10^{15} fissions/liter = 1.5×10^{17} fissions.

10-minute yield = 150 liters x 1.5×10^{16} fissions/liter = 2.25×10^{18} fissions.

8-hour yield = $1.5 \times 10^{17} \times 30 = 4.5 \times 10^{18}$ fissions.