MATERIAL SCIENCE
Module 4
Brittle Fracture

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REFERENCES

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TERMINAL OBJECTIVE

1.0 Without references, **EXPLAIN** the importance of controlling heatup and cooldown rates of the primary coolant system.

ENABLING OBJECTIVES

1.1 **DEFINE** the following terms:

  a. Ductile fracture
  b. Brittle fracture
  c. Nil-ductility Transition (NDT) Temperature

1.2 **DESCRIBE** the two changes made to reactor pressure vessels to decrease NDT.

1.3 **STATE** the effect grain size and irradiation have on a material's NDT.

1.4 **LIST** the three conditions necessary for brittle fracture to occur.

1.5 **STATE** the three conditions that tend to mitigate crack initiation.

1.6 **LIST** the five factors that determine the fracture toughness of a material.

1.7 Given a stress-temperature diagram, **IDENTIFY** the following points:

  a. NDT (with no flaw)
  b. NDT (with flaw)
  c. Fracture transition elastic point
  d. Fracture transition plastic point

1.8 **STATE** the two bases used for developing a minimum pressurization-temperature curve.

1.9 **EXPLAIN** a typical minimum pressure-temperature curve including:

  a. Location of safe operating region
  b. The way the curve will shift due to irradiation

ENABLING OBJECTIVES (Cont.)

1.10 **LIST** the normal actions taken, in sequence, if the minimum pressurization-temperature curve is exceeded during critical operations.

1.11 **STATE** the precaution for hydrostatic testing.

1.12 **IDENTIFY** the basis used for determining heatup and cooldown rate limits.

1.13 **IDENTIFY** the three components that will set limits on the heatup and cooldown rates.

1.14 **STATE** the action typically taken upon discovering the heatup or cooldown rate has been exceeded.

1.15 **STATE** the reason for using soak times.

1.16 **STATE** when soak times become very significant.

BRITTLE FRACTURE MECHANISM

Personnel need to understand brittle fracture. This type of fracture occurs under specific conditions without warning and can cause major damage to plant materials.

EO 1.1 **DEFINE the following terms:**

- **a. Ductile fracture**
- **b. Brittle fracture**
- **c. Nil-ductility Transition (NDT) Temperature**

EO 1.2 **DESCRIBE the two changes made to reactor pressure vessels to decrease NDT.**

EO 1.3 **STATE the effect grain size and irradiation have on a material's NDT.**

EO 1.4 **LIST the three conditions necessary for brittle fracture to occur.**

EO 1.5 **STATE the three conditions that tend to mitigate crack initiation.**

EO 1.6 **LIST the five factors that determine the fracture toughness of a material.**

EO 1.7 **Given a stress-temperature diagram, IDENTIFY the following points:**

- **a. NDT (with no flaw)**
- **b. NDT (with flaw)**
- **c. Fracture transition elastic point**
- **d. Fracture transition plastic point**

Brittle Fracture Mechanism

Metals can fail by ductile or brittle fracture. Metals that can sustain substantial plastic strain or deformation before fracturing exhibit *ductile fracture*. Usually a large part of the plastic flow is concentrated near the fracture faces.

Metals that fracture with a relatively small or negligible amount of plastic strain exhibit *brittle fracture*. Cracks propagate rapidly. Brittle failure results from *cleavage* (splitting along definite planes). Ductile fracture is better than brittle fracture, because ductile fracture occurs over a period of time, where as brittle fracture is fast, and can occur (with flaws) at lower stress levels than a ductile fracture. Figure 1 shows the basic types of fracture.

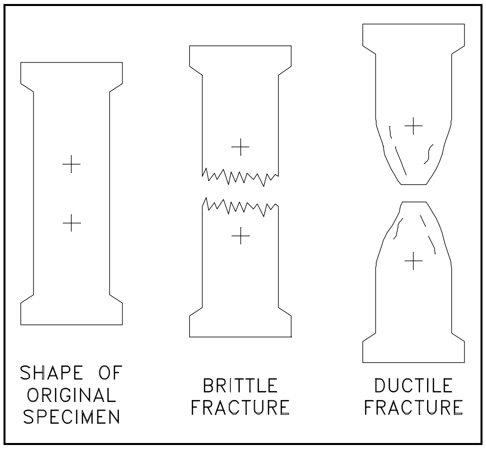

Figure 1 Basic Fracture Types

Brittle cleavage fracture is of the most concern in this module. *Brittle cleavage fracture* occurs in materials with a high strain-hardening rate and relatively low cleavage strength or great sensitivity to multi-axial stress.

Many metals that are ductile under some conditions become brittle if the conditions are altered. The effect of temperature on the nature of the fracture is of considerable importance. Many steels exhibit ductile fracture at elevated temperatures and brittle fracture at low temperatures. The temperature above which a material is ductile and below which it is brittle is known as the *Nil-Ductility Transition (NDT) temperature*. This temperature is not precise, but varies according to prior mechanical and heat treatment and the nature and amounts of impurity elements. It is determined by some form of drop-weight test (for example, the Izod or Charpy tests).

Ductility is an essential requirement for steels used in the construction of reactor vessels; therefore, the NDT temperature is of significance in the operation of these vessels. Small grain size tends to increase ductility and results in a decrease in NDT temperature. Grain size is controlled by heat treatment in the specifications and manufacturing of reactor vessels. The NDT temperature can also be lowered by small additions of selected alloying elements such as nickel and manganese to low-carbon steels.

Of particular importance is the shifting of the NDT temperature to the right (Figure 2), when the reactor vessel is exposed to fast neutrons. The reactor vessel is continuously exposed to fast neutrons that escape from the core. Consequently, during operation the reactor vessel is subjected to an increasing fluence (flux) of fast neutrons, and as a result the NDT temperature increases steadily. It is not likely that the NDT temperature will approach the normal operating temperature of the steel. However, there is a possibility that when the reactor is being shut down or during an abnormal cooldown, the temperature may fall below the NDT value while the internal pressure is still high. The reactor vessel is susceptible to brittle fracture at this point. Therefore, special attention must be given to the effect of neutron irradiation on the NDT temperature of the steels used in fabricating reactor pressure vessels. The Nuclear Regulatory Commission requires that a reactor vessel material surveillance program be conducted in water-cooled power reactors in accordance with ASTM Standards (designation E 185-73).

Pressure vessels are also subject to cyclic stress. *Cyclic stress* arises from pressure and/or temperature cycles on the metal. Cyclic stress can lead to fatigue failure. Fatigue failure, discussed in more detail in Module 5, can be initiated by microscopic cracks and notches and even by grinding and machining marks on the surface. The same (or similar) defects also favor brittle fracture.

Stress-Temperature Curves

One of the biggest concerns with brittle fracture is that it can occur at stresses well below the yield strength (stress corresponding to the transition from elastic to plastic behavior) of the material, provided certain conditions are present. These conditions are: a flaw such as a crack; a stress of sufficient intensity to develop a small deformation at the crack tip; and a temperature low enough to promote brittle fracture. The relationship between these conditions is best described using a generalized stress-temperature diagram for crack initiation and arrest as shown in Figure 2.

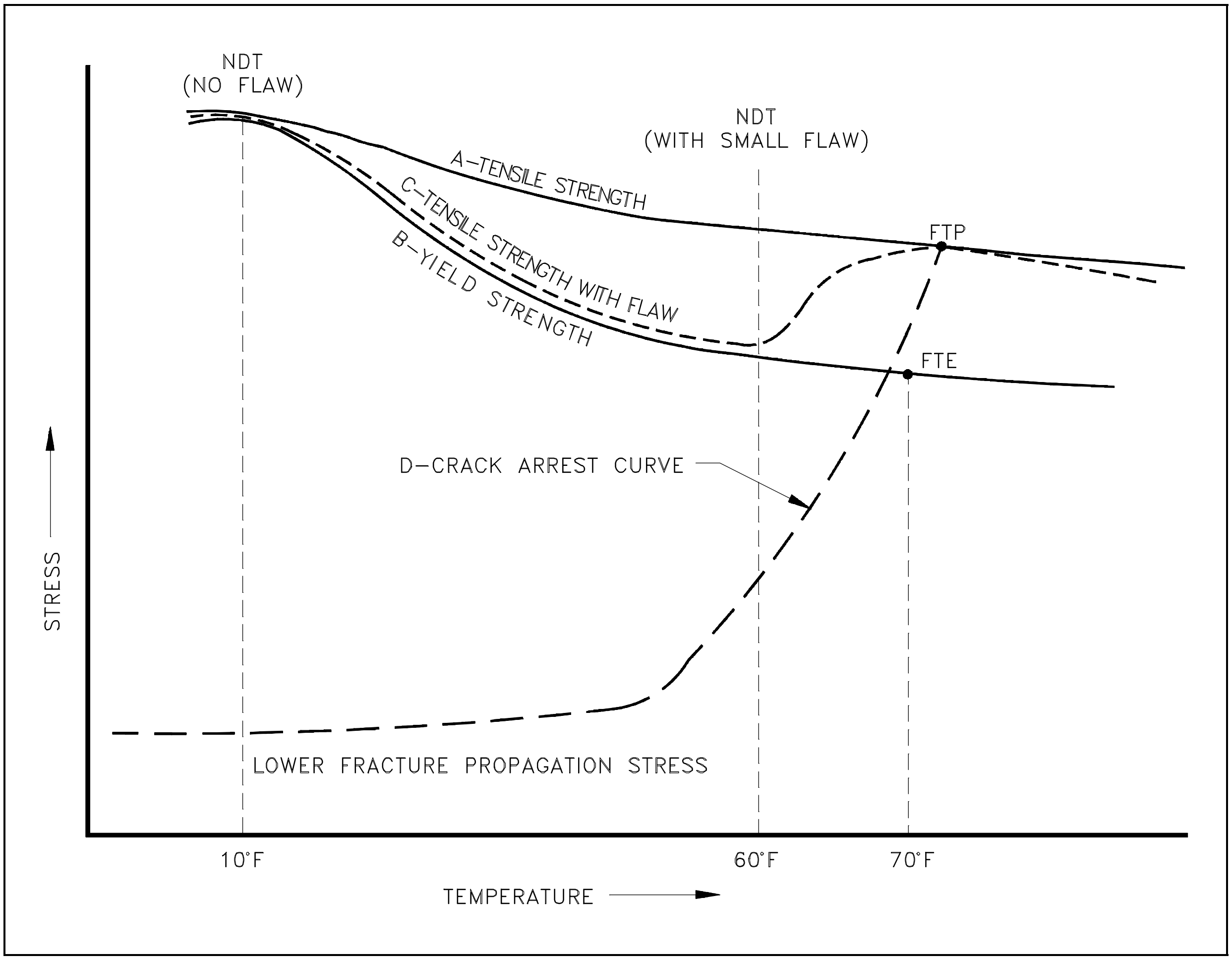

Figure 2 Stress-Temperature Diagram for Crack Initiation and Arrest

Figure 2 illustrates that as the temperature goes down, the tensile strength (Curve A) and the yield strength (Curve B) increase. The increase in tensile strength, sometimes known as the ultimate strength (a maximum of increasing strain on the stress-strain curve), is less than the increase in the yield point. At some low temperature, on the order of 10°F for carbon steel, the yield strength and tensile strength coincide. At this temperature and below, there is no yielding when a failure occurs. Hence, the failure is brittle. The temperature at which the yield and tensile strength coincide is the NDT temperature.

When a small flaw is present, the tensile strength follows the dashed Curve C. At elevated temperatures, Curves A and C are identical. At lower temperatures, approximately 50°F above the NDT temperature for material with no flaws, the tensile strength curve drops to the yield curve and then follows the yield curve to lower temperatures. At the point where Curves C and B meet, there is a new NDT temperature. Therefore, if a flaw exists, any failure at a temperature equal or below the NDT temperature for flawed material will be brittle.

Crack Initiation and Propagation

As discussed earlier in this chapter, brittle failure generally occurs because a flaw or crack propagates throughout the material. The start of a fracture at low stresses is determined by the cracking tendencies at the tip of the crack. If a plastic flaw exists at the tip, the structure is not endangered because the metal mass surrounding the crack will support the stress. When brittle fracture occurs (under the conditions for brittle fracture stated above), the crack will initiate and propagate through the material at great speeds (speed of sound). It should be noted that smaller grain size, higher temperature, and lower stress tend to mitigate crack initiation. Larger grain size, lower temperatures, and higher stress tend to favor crack propagation. There is a stress level below which a crack will not propagate at any temperature. This is called the lower fracture propagation stress. As the temperature increases, a higher stress is required for a crack to propagate. The relationship between the temperature and the stress required for a crack to propagate is called the crack arrest curve, which is shown on Figure 2 as Curve D. At temperatures above that indicated on this curve, crack propagation will not occur.

Fracture Toughness

Fracture toughness is an indication of the amount of stress required to propagate a preexisting flaw. The fracture toughness of a metal depends on the following factors.

a. Metal composition
b. Metal temperature
c. Extent of deformations to the crystal structure
d. Metal grain size
e. Metal crystalline form

The intersection of the crack arrest curve with the yield curve (Curve B) is called the *fracture transition elastic* (FTE) *point*. The temperature corresponding to this point is normally about 60°F above the NDT temperature. This temperature is also known as the Reference Temperature - Nil-ductility Transition (RT_{NDT}) and is determined in accordance with ASME Section III (1974 edition), NB 2300. The FTE is the temperature above which plastic deformation accompanies all fractures or the highest temperature at which fracture propagation can occur under purely elastic loads. The intersection of the crack arrest curve (Curve D) and the tensile strength or ultimate strength, curve (Curve A) is called the *fracture transition plastic* (FTP) *point*. The temperature corresponding with this point is normally about 120°F above the NDT temperature. Above this temperature, only ductile fractures occur.

Figure 3 is a graph of stress versus temperature, showing fracture initiation curves for various flaw sizes.

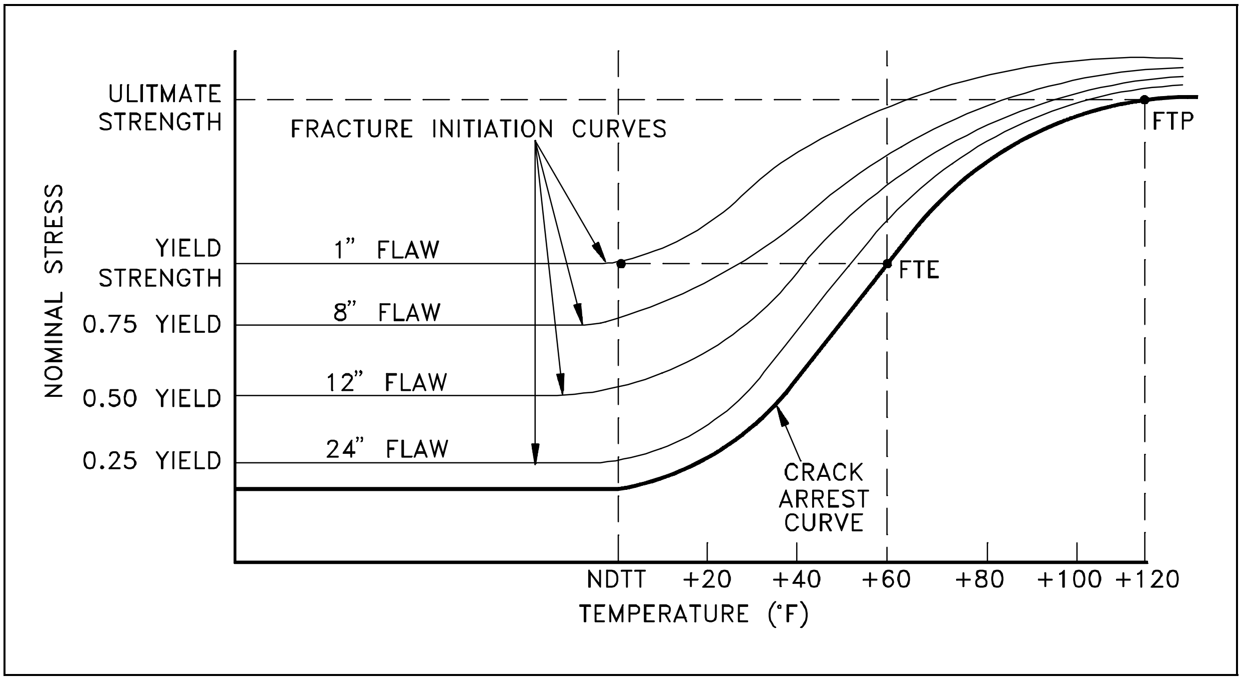

Figure 3 Fracture Diagram

It is clear from the above discussion that we must operate above the NDT temperature to be certain that no brittle fracture can occur. For greater safety, it is desirable that operation be limited above the FTE temperature, or NDT + 60°F. Under such conditions, no brittle fracture can occur for purely elastic loads.

As previously discussed, irradiation of the pressure vessel can raise the NDT temperature over the lifetime of the reactor pressure vessel, restricting the operating temperatures and stress on the vessel. It should be clear that this increase in NDT can lead to significant operating restrictions, especially after 25 years to 30 years of operation where the NDT can raise 200°F to 300°F. Thus, if the FTE was 60°F at the beginning of vessel life and a change in the NDT of 300°F occurred over a period of time, the reactor coolant would have to be raised to more than 360°F before full system pressure could be applied.

Summary

The important information in this chapter is summarized below.

Brittle Fracture Summary

- Ductile fracture is exhibited when metals can sustain substantial plastic strain or deformation before fracturing.

- Brittle fracture is exhibited when metals fracture with a relatively small or negligible amount of plastic strain.

- Nil-Ductility Transition (NDT) temperature is the temperature above which a material is ductile and below which it is brittle.

- Changes made to decrease NDT include:

  Use of smaller grain size in metals

  Small additions of selected alloying elements such as nickel and manganese to low-carbon steels

- NDT decreases due to smaller grain size and increases due to irradiation

- Brittle fracture requires three conditions:

  Flaw such as a crack
  Stress sufficient to develop a small deformation at the crack tip
  Temperature at or below NDT

- Conditions to mitigate crack initiation:

  Smaller grain size
  Higher temperature
  Lower stress levels

- Factors determining fracture toughness of a metal include:

  Metal composition
  Metal temperature
  Extent of deformations to the crystal structure
  Metal grain size
  Metal crystalline form

MINIMUM PRESSURIZATION-TEMPERATURE CURVES

Plant operations are effected by the minimum pressurization-temperature curves. Personnel need to understand the information that is associated with the curves to better operate the plant.

EO 1.8 **STATE the two bases used for developing a minimum pressurization-temperature curve.**

EO 1.9 **EXPLAIN a typical minimum pressure-temperature curve including:**

- **a. Location of safe operating region**
- **b. The way the curve will shift due to irradiation**

EO 1.10 **LIST the normal actions taken, in sequence, if the minimum pressurization-temperature curve is exceeded during critical operations.**

EO 1.11 **STATE the precaution for hydrostatic testing.**

MPT Definition and Basis

Minimum pressurization-temperature (MPT) *curves* specify the temperature and pressure limitations for reactor plant operation. They are based on reactor vessel and head stress limitations and the need to preclude reactor vessel and head brittle fracture. Figure 4 shows some pressure-temperature operating curves for a pressurized water reactor (PWR) Primary Coolant System (PCS).

Note that the safe operating region is to the right of the reactor vessel MPT curve. The reactor vessel MPT curve ensures adequate operating margin away from the crack arrest curve discussed above. The curves used by operations also incorporate instrument error to ensure adequate safety margin. Because of the embrittling effects of neutron irradiation, the MPT curve will shift to the right over core life to account for the increased brittleness or decreased ductility. Figure 4 also contains pressurizer and steam generator operating curves. Operating curves may also include surge line and primary coolant pump operating limitations. The MPT relief valve setting prevents exceeding the NDT limit for pressure when the PCS is cold and is set below the lowest limit of the reactor vessel MPT curve.

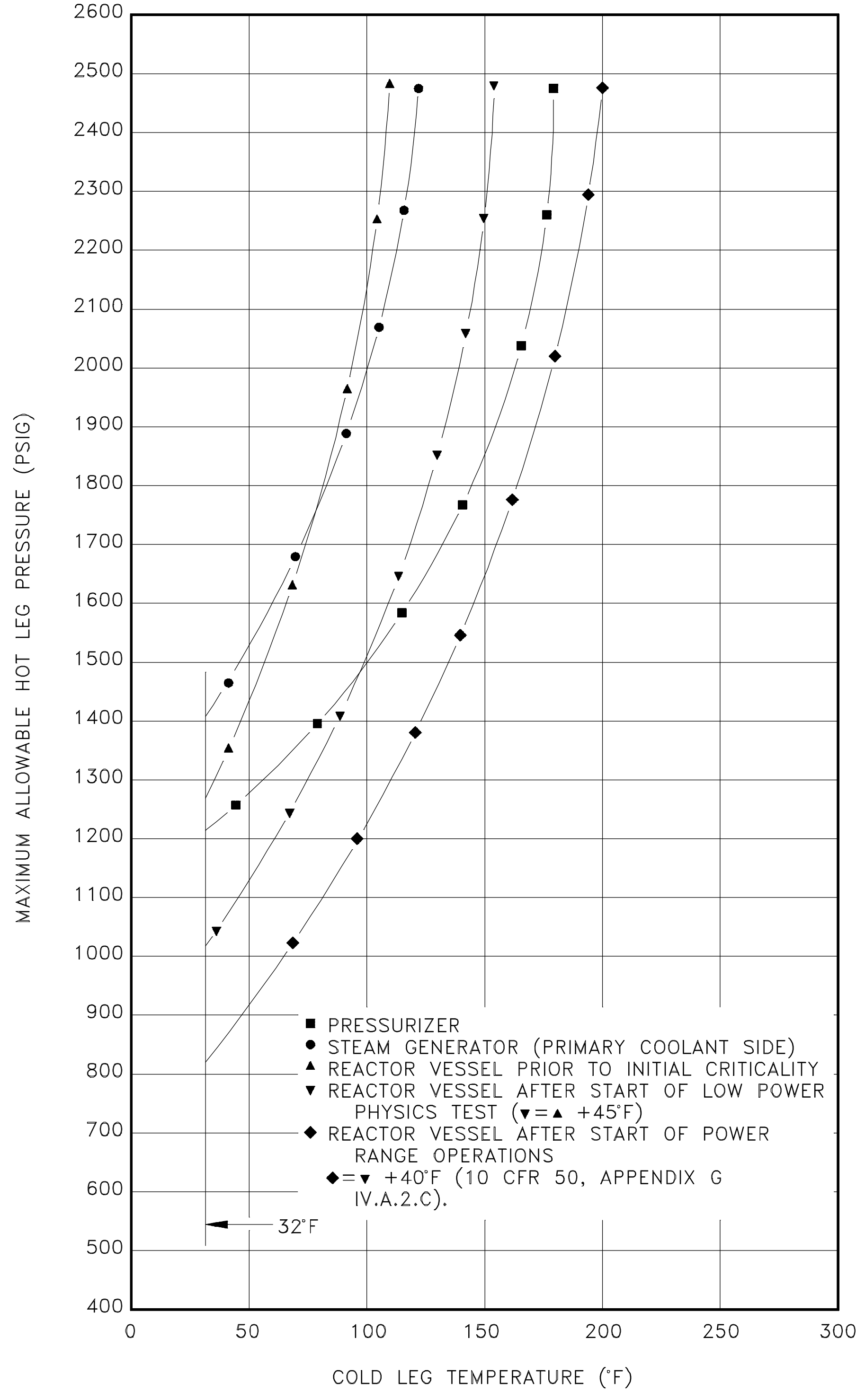

Figure 4 PCS Temperature vs. Pressure for Normal Operation

If the limit of the MPT curve is exceeded during critical operation, the usual action is to scram the reactor, cool down and depressurize the PCS, and conduct an engineering evaluation prior to further plant operation.

During hydrostatic testing, minimum pressurization temperature precautions include making sure that desired hydrostatic pressure is consistent with plant temperatures so that excessive stress does not occur. Figure 5 shows MPT curves for hydrostatic testing of a PWR PCS. The safe operating region is to the right of the MPT curves. Other special hydrostatic limits may also apply during testing.

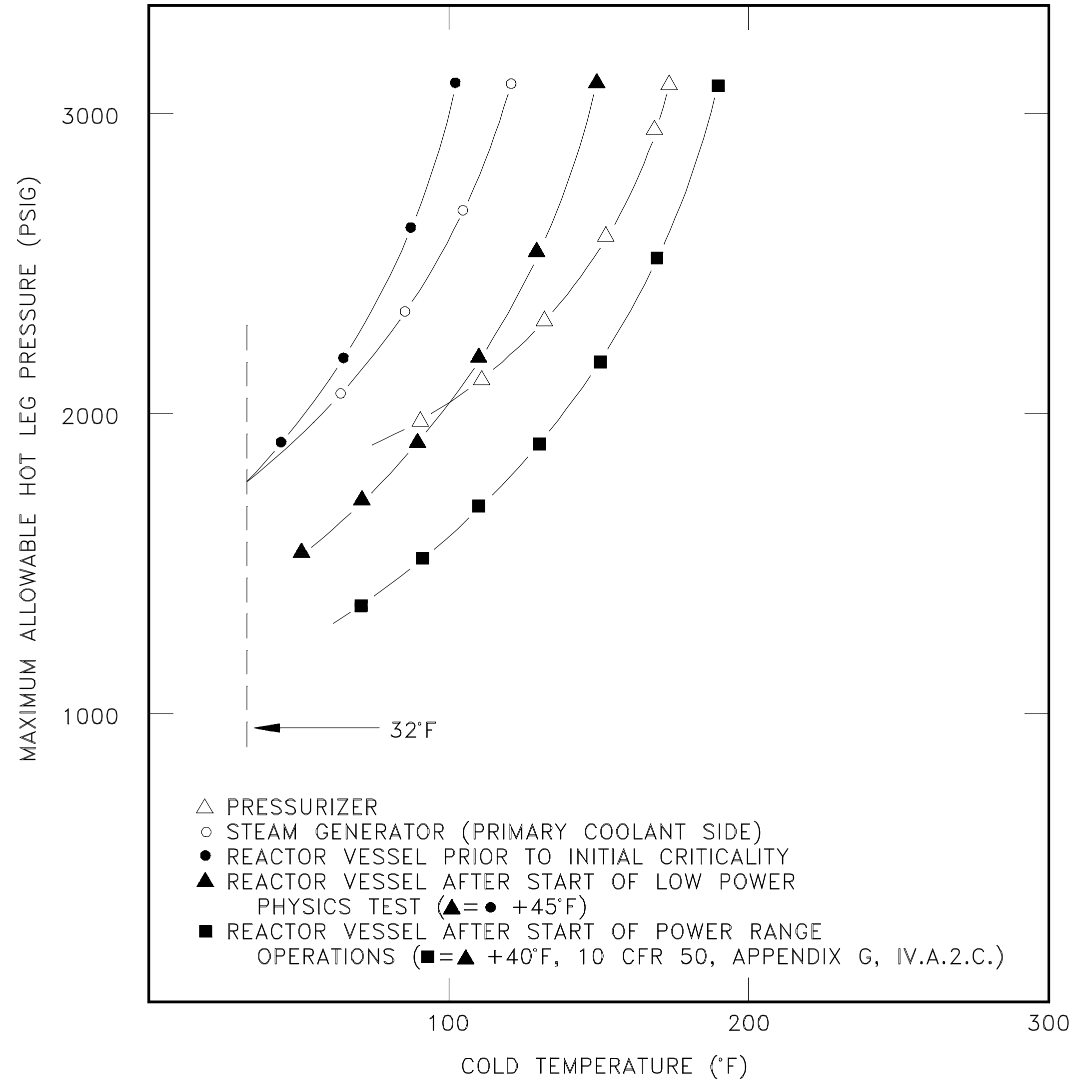

Figure 5 PCS Temperature vs. Hydrotest Pressure

Summary

The important information in this chapter is summarized below.

Minimum Pressurization-Temperature Curves Summary

- MPT curves are based on reactor vessel and head stress limitations, and the need to prevent reactor vessel and head brittle fracture.

- MPT curve safe operating region is to the right of the curve.

- MPT curve will shift to the right due to irradiation.

- Normal actions if MPT curves are exceeded during critical operation are:

    Scram reactor

    Cool down and depressurize

    Conduct engineering evaluation prior to further plant operation

- The precaution to be observed when performing a hydrostatic test is to make sure the pressure is consistent with plant temperatures.

HEATUP AND COOLDOWN RATE LIMITS

Personnel operating a reactor plant must be aware of the heatup and cooldown rates for the system. If personnel exceed these rates, major damage could occur under certain conditions.

EO 1.12 IDENTIFY the basis used for determining heatup and cooldown rate limits.

EO 1.13 IDENTIFY the three components that will set limits on the heatup and cooldown rates.

EO 1.14 STATE the action typically taken upon discovering the heatup or cooldown rate has been exceeded.

EO 1.15 STATE the reason for using soak times.

EO 1.16 STATE when soak times become very significant.

Basis

Heatup and cooldown rate limits, as shown in Figure 6, are based upon the impact on the future fatigue life of the plant. The heatup and cooldown limits ensure that the plant's fatigue life is equal to or greater than the plant's operational life. Large components such as flanges, the reactor vessel head, and even the reactor vessel itself are the limiting components. Usually the most limiting component will set the heatup and cooldown rates.

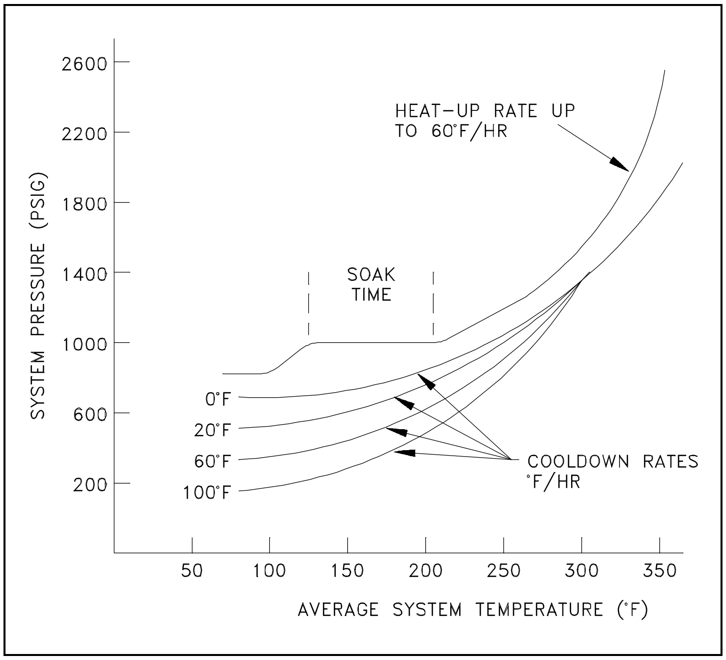

Figure 6 Heatup and Cooldown Rate Limits

Thermal stress imposed by a rapid temperature change (a fast ramp or even a step change) of approximately 20°F (depending upon the plant) is insignificant (10^6 cycles allowed depending upon component) and has no effect on the design life of the plant.

Exceeding Heatup and Cooldown Rates

Usually, exceeding heatup or cooldown limits or other potential operational thermal transient limitations is not an immediate hazard to continued operation and only requires an assessment of the impact on the future fatigue life of the plant. However, this may depend upon the individual plant and its limiting components.

Individual components, such as the pressurizer, may have specific heatup and cooldown limitations that, in most cases, are less restrictive than for the PCS.

Because of the cooldown transient limitations of the PCS, the reactor should be shut down in an orderly manner. Cooldown of the PCS from full operating temperature to 200°F or less requires approximately 24 hours (depending upon cooldown limit rates) as a minimum. Requirements may vary from plant to plant.

Soak Times

Soak times may be required when heating up the PCS, especially when large limiting components are involved in the heatup. Soak times are used so that heating can be carefully controlled. In this manner thermal stresses are minimized. An example of a soak time is to heat the reactor coolant to a specified temperature and to stay at that temperature for a specific time period. This allows the metal in a large component, such as the reactor pressure vessel head, to heat more evenly from the hot side to the cold side, thus limiting the thermal stress across the head. Soak time becomes very significant when the PCS is at room temperature or below and very close to its RT_{NDT} temperature limitations.

Summary

The important information in this chapter is summarized below.

Heatup-Cooldown Rate Limits Summary

- Heatup and cooldown rate limits are based upon impact on the future fatigue life of the plant. The heatup and cooldown rate limits ensure that the plant's fatigue life is equal to or greater than the plant's operational life.

- Large components such as flanges, reactor vessel head, and the vessel itself are the limiting components.

- Usually exceeding the heatup or cooldown rate limits requires only an assessment of the impact on the future fatigue life of the plant.

- Soak times:

  May be required when heating large components

  Used to minimize thermal stresses by controlling the heating rate

  Become very significant if system is at room temperature or below and very close to RT_{NDT} temperature limitations