INSTRUMENTATION AND CONTROL
Module 1
Temperature Detectors

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TERMINAL OBJECTIVE

1.0 Given a temperature instrument, **RELATE** the associated fundamental principles, including possible failure modes, to that instrument.

ENABLING OBJECTIVES

1.1 **DESCRIBE** the construction of a basic RTD including:
- a. Major component arrangement
- b. Materials used

1.2 **EXPLAIN** how RTD resistance varies for the following:
- a. An increase in temperature
- b. A decrease in temperature

1.3 **EXPLAIN** how an RTD provides an output representative of the measured temperature.

1.4 **DESCRIBE** the basic construction of a thermocouple including:
- a. Major component arrangement
- b. Materials used

1.5 **EXPLAIN** how a thermocouple provides an output representative of the measured temperature.

1.6 **STATE** the three basic functions of temperature detectors.

1.7 **DESCRIBE** the two alternate methods of determining temperature when the normal temperature sensing devices are inoperable.

1.8 **STATE** the two environmental concerns which can affect the accuracy and reliability of temperature detection instrumentation.

1.9 Given a simplified schematic diagram of a basic bridge circuit, **STATE** the purpose of the following components:
- a. R_1 and R_2
- b. R_x
- c. Adjustable resistor
- d. Sensitive ammeter

ENABLING OBJECTIVES (Cont.)

1.10 **DESCRIBE** the bridge circuit conditions that create a balanced bridge.

1.11 Given a block diagram of a basic temperature instrument detection and control system, **STATE** the purpose of the following blocks:
   a. RTD
   b. Bridge circuit
   c. DC-AC converter
   d. Amplifier
   e. Balancing motor/mechanical linkage

1.12 **DESCRIBE** the temperature instrument indication(s) for the following circuit faults:
   a. Short circuit
   b. Open circuit

1.13 **EXPLAIN** the three methods of bridge circuit compensation for changes in ambient temperature.

RESISTANCE TEMPERATURE DETECTORS (RTDs)

The resistance of certain metals will change as temperature changes. This characteristic is the basis for the operation of an RTD.

EO 1.1 DESCRIBE the construction of a basic RTD including:
- **a. Major component arrangement**
- **b. Materials used**

EO 1.2 EXPLAIN how RTD resistance varies for the following:
- **a. An increase in temperature**
- **b. A decrease in temperature**

EO 1.3 EXPLAIN how an RTD provides an output representative of the measured temperature.

Temperature

The hotness or coldness of a piece of plastic, wood, metal, or other material depends upon the molecular activity of the material. Kinetic energy is a measure of the activity of the atoms which make up the molecules of any material. Therefore, temperature is a measure of the kinetic energy of the material in question.

Whether you want to know the temperature of the surrounding air, the water cooling a car's engine, or the components of a nuclear facility, you must have some means to measure the kinetic energy of the material. Most temperature measuring devices use the energy of the material or system they are monitoring to raise (or lower) the kinetic energy of the device. A normal household thermometer is one example. The mercury, or other liquid, in the bulb of the thermometer expands as its kinetic energy is raised. By observing how far the liquid rises in the tube, you can tell the temperature of the measured object.

Because temperature is one of the most important parameters of a material, many instruments have been developed to measure it. One type of detector used is the resistance temperature detector (RTD). The RTD is used at many DOE nuclear facilities to measure temperatures of the process or materials being monitored.

RTD Construction

The RTD incorporates pure metals or certain alloys that increase in resistance as temperature increases and, conversely, decrease in resistance as temperature decreases. RTDs act somewhat like an electrical transducer, converting changes in temperature to voltage signals by the measurement of resistance. The metals that are best suited for use as RTD sensors are pure, of uniform quality, stable within a given range of temperature, and able to give reproducible resistance-temperature readings. Only a few metals have the properties necessary for use in RTD elements.

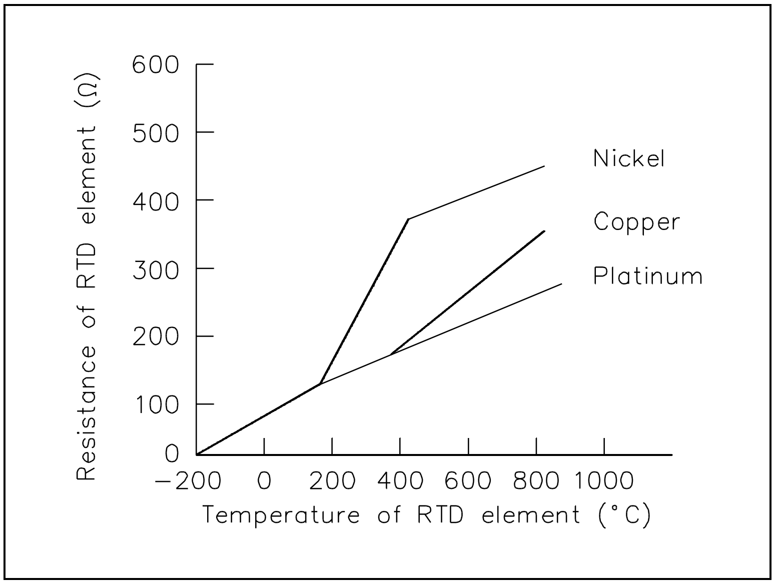

Figure 1 Electrical Resistance-Temperature Curves

RTD elements are normally constructed of platinum, copper, or nickel. These metals are best suited for RTD applications because of their linear resistance-temperature characteristics (as shown in Figure 1), their high coefficient of resistance, and their ability to withstand repeated temperature cycles.

The coefficient of resistance is the change in resistance per degree change in temperature, usually expressed as a percentage per degree of temperature. The material used must be capable of being drawn into fine wire so that the element can be easily constructed.

RTD elements are usually long, spring-like wires surrounded by an insulator and enclosed in a sheath of metal. Figure 2 shows the internal construction of an RTD.

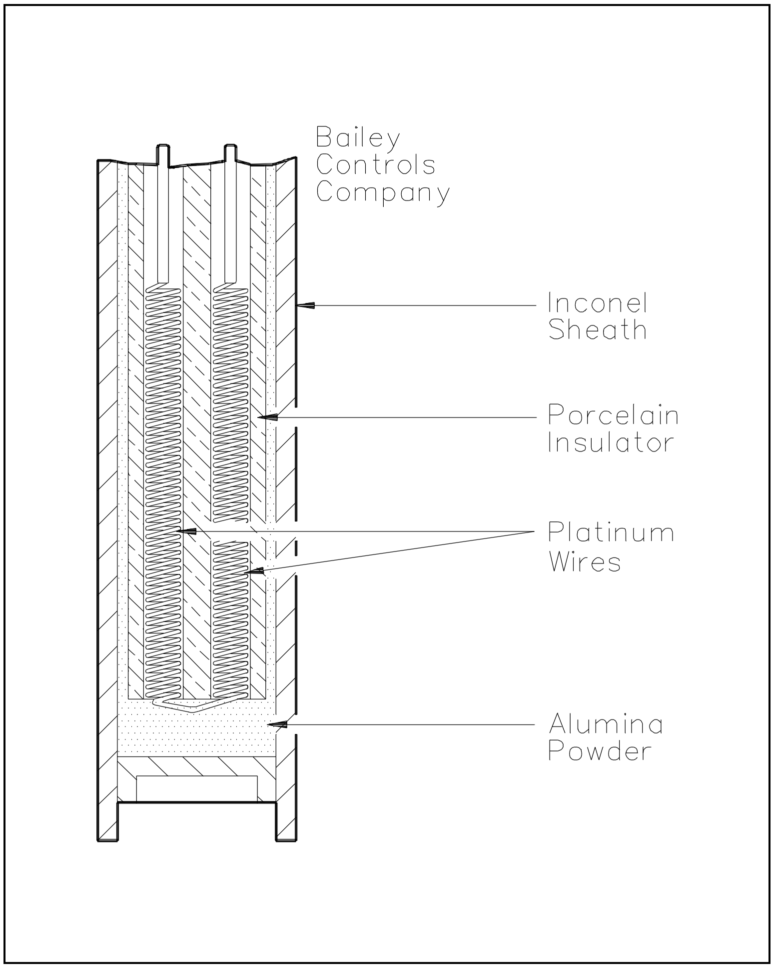

Figure 2 Internal Construction of a Typical RTD

This particular design has a platinum element that is surrounded by a porcelain insulator. The insulator prevents a short circuit between the wire and the metal sheath.

Inconel, a nickel-iron-chromium alloy, is normally used in manufacturing the RTD sheath because of its inherent corrosion resistance. When placed in a liquid or gas medium, the Inconel sheath quickly reaches the temperature of the medium. The change in temperature will cause the platinum wire to heat or cool, resulting in a proportional change in resistance.

This change in resistance is then measured by a precision resistance measuring device that is calibrated to give the proper temperature reading. This device is normally a bridge circuit, which will be covered in detail later in this text.

Figure 3 shows an RTD protective well and terminal head. The well protects the RTD from damage by the gas or liquid being measured. Protecting wells are normally made of stainless steel, carbon steel, Inconel, or cast iron, and they are used for temperatures up to 1100°C.

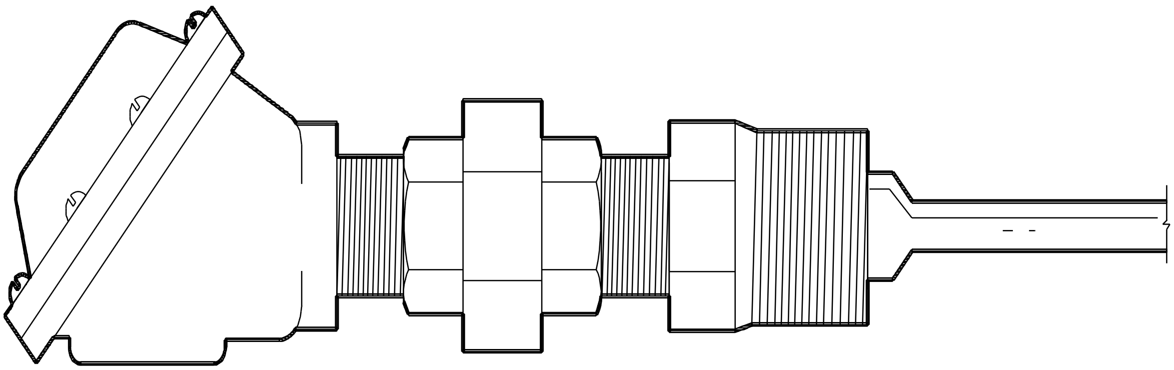

Figure 3 RTD Protective Well and Terminal Head

Summary

Resistance temperature detectors (RTDs) are summarized below.

RTD Summary

- The resistance of an RTD varies directly with temperature:
  - As temperature increases, resistance increases.
  - As temperature decreases, resistance decreases.
- RTDs are constructed using a fine, pure, metallic, spring-like wire surrounded by an insulator and enclosed in a metal sheath.
- A change in temperature will cause an RTD to heat or cool, producing a proportional change in resistance. The change in resistance is measured by a precision device that is calibrated to give the proper temperature reading.

THERMOCOUPLES

The thermocouple is a device that converts thermal energy into electrical energy.

EO 1.4 DESCRIBE the basic construction of a thermocouple including:
a. Major component arrangement
b. Materials used

EO 1.5 EXPLAIN how a thermocouple provides an output representative of the measured temperature.

Thermocouple Construction

A thermocouple is constructed of two dissimilar metal wires joined at one end. When one end of each wire is connected to a measuring instrument, the thermocouple becomes a sensitive and highly accurate measuring device. Thermocouples may be constructed of several different combinations of materials. The performance of a thermocouple material is generally determined by using that material with platinum. The most important factor to be considered when selecting a pair of materials is the "thermoelectric difference" between the two materials. A significant difference between the two materials will result in better thermocouple performance. Figure 4 illustrates the characteristics of the more commonly used materials when used with platinum.

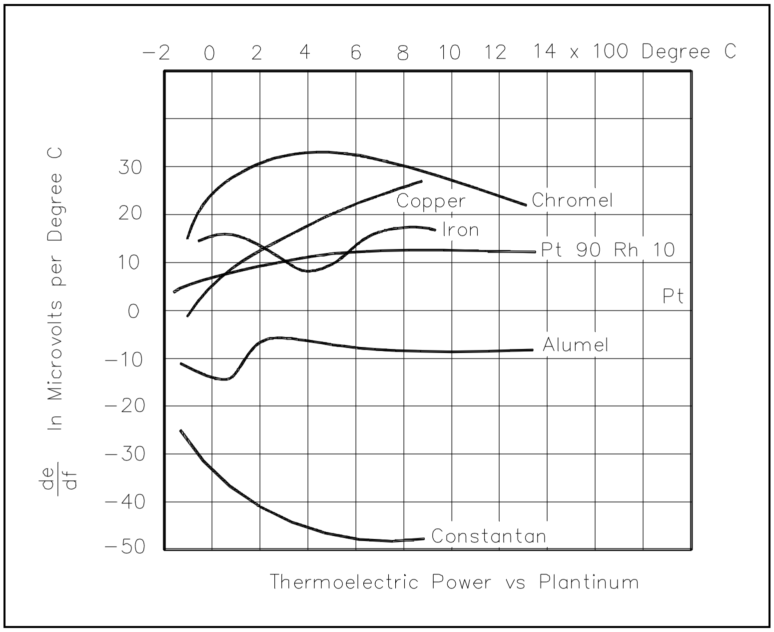

Figure 4 Thermocouple Material Characteristics When Used with Platinum

Other materials may be used in addition to those shown in Figure 4. For example: Chromel-Constantan is excellent for temperatures up to 2000°F; Nickel/Nickel-Molybdenum sometimes replaces Chromel-Alumel; and Tungsten-Rhenium is used for temperatures up to 5000°F. Some combinations used for specialized applications are Chromel-White Gold, Molybdenum-Tungsten, Tungsten-Iridium, and Iridium/Iridium-Rhodium.

Figure 5 shows the internal construction of a typical thermocouple. The leads of the thermocouple are encased in a rigid metal sheath. The measuring junction is normally formed at the bottom of the thermocouple housing. Magnesium oxide surrounds the thermocouple wires to prevent vibration that could damage the fine wires and to enhance heat transfer between the measuring junction and the medium surrounding the thermocouple.

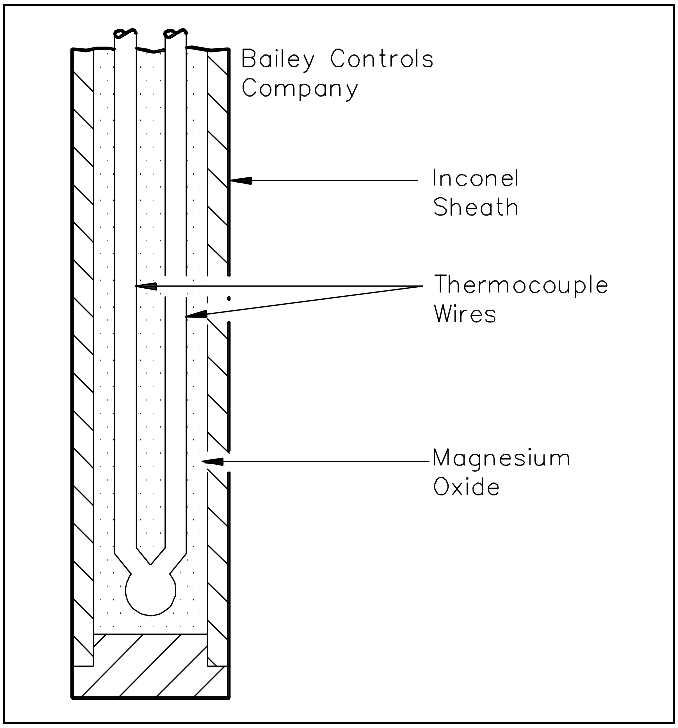

Figure 5 Internal Construction of a Typical Thermocouple

Thermocouple Operation

Thermocouples will cause an electric current to flow in the attached circuit when subjected to changes in temperature. The amount of current that will be produced is dependent on the temperature difference between the measurement and reference junction; the characteristics of the two metals used; and the characteristics of the attached circuit. Figure 6 illustrates a simple thermocouple circuit.

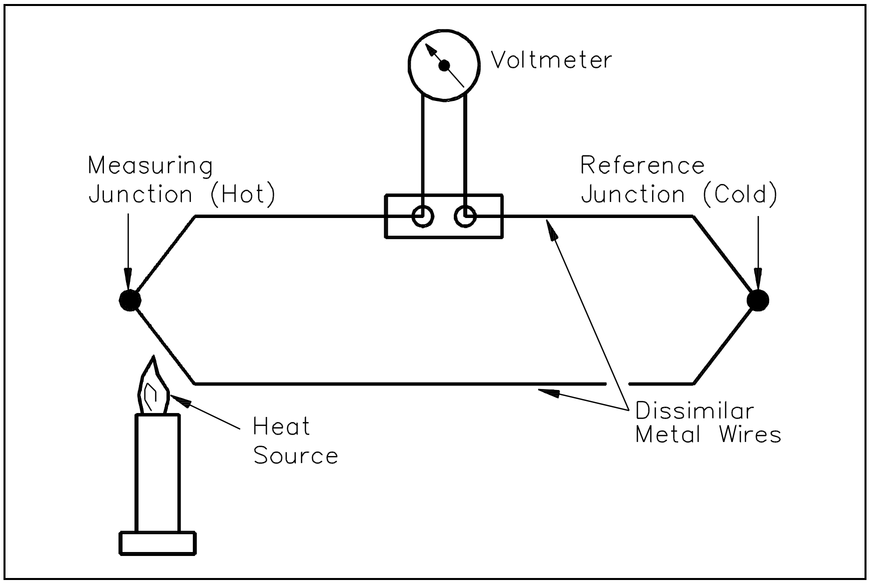

Figure 6 Simple Thermocouple Circuit

Heating the measuring junction of the thermocouple produces a voltage which is greater than the voltage across the reference junction. The difference between the two voltages is proportional to the difference in temperature and can be measured on the voltmeter (in millivolts). For ease of operator use, some voltmeters are set up to read out directly in temperature through use of electronic circuity.

Other applications provide only the millivolt readout. In order to convert the millivolt reading to its corresponding temperature, you must refer to tables like the one shown in Figure 7. These tables can be obtained from the thermocouple manufacturer, and they list the specific temperature corresponding to a series of millivolt readings.

Temperatures (°C) (IPTS 1968). Reference Junction 0°C.

°C	0	10	20	30	40	50	60	70	80	90	100	°C
					Thermoelectric Voltage in Absolute Millivolts							
- 0	0.000	-0.053	-0.103	-0.150	-0.194	-0.236						- 0
+ 0	0.000	0.055	0.113	0.173	0.235	0.299	0.365	0.432	0.502	0.573	0.645	+ 0
100	0.645	0.719	0.795	0.872	0.950	1.029	1.109	1.190	1.273	1.356	1.440	100
200	1.440	1.525	1.611	1.698	1.785	1.873	1.962	2.051	2.141	2.232	2.323	200
300	2.323	2.414	2.506	2.599	2.692	2.786	2.880	2.974	3.069	3.164	3.260	300
400	3.260	3.356	3.452	3.549	3.645	3.743	3.840	3.938	4.036	4.135	4.234	400
500	4.234	4.333	4.432	4.532	4.632	4.732	4.332	4.933	5.034	5.136	5.237	500
600	5.237	5.339	5.442	5.544	5.648	5.751	5.855	5.960	6.064	6.169	6.274	600
700	6.274	6.380	6.486	6.592	6.699	6.805	6.913	7.020	7.128	7.236	7.345	700
800	7.345	7.454	7.563	7.672	7.782	7.892	8.003	8.114	8.225	8.336	8.448	800
900	8.448	8.560	8.673	8.786	8.899	9.012	9.126	9.240	9.355	9.470	9.585	900
1,000	9.585	9.700	9.816	9.932	10.048	10.165	10.282	10.400	10.517	10.635	10.754	1,000
1,100	10.754	10.872	10.991	11.110	11.229	11.348	11.467	11.587	11.707	11.827	11.947	1,100
1,200	11.947	12.067	12.188	12.308	12.429	12.550	12.671	12.792	12.913	13.034	13.155	1,200
1,300	13.155	13.276	13.397	13.519	13.640	13.761	13.883	14.004	14.125	14.247	14.368	1,300
1,400	14.368	14.489	14.610	14.731	14.852	14.973	15.094	15.215	15.336	15.456	15.576	1,400
1,500	15.576	15.697	15.817	15.937	16.057	16.176	16.296	16.415	16.534	16.653	16.771	1,500
1,600	16.771	16.890	17.008	17.125	17.243	17.360	17.477	17.594	17.711	17.826	17.942	1,600
1,700	17.942	18.058	18.170	18.282	18.394	18.504	18.612					1,700
°C	0	10	20	30	40	50	60	70	80	90	100	°C

Figure 7 Temperature-vs-Voltage Reference Table

Summary

Thermocouples are summarized below.

Thermocouple Summary

- A thermocouple is constructed of two dissimilar wires joined at one end and encased in a metal sheath.
- The other end of each wire is connected to a meter or measuring circuit.
- Heating the measuring junction of the thermocouple produces a voltage that is greater than the voltage across the reference junction.
- The difference between the two voltages is proportional to the difference in temperature and can be measured on a voltmeter.

FUNCTIONAL USES OF TEMPERATURE DETECTORS

Temperature sensing devices, such as RTDs and thermocouples, provide necessary temperature indications for the safe and continued operation of the DOE facility fluid systems. These temperature indications may include:

- *Reactor hot and cold leg temperatures*
- *Pressurizer temperature*
- *Purification demineralizer inlet temperature*
- *Cooling water to and from various components*
- *Secondary feed temperature*

EO 1.6 STATE the three basic functions of temperature detectors.

EO 1.7 DESCRIBE the two alternate methods of determining temperature when the normal temperature sensing devices are inoperable.

EO 1.8 STATE the two environmental concerns which can affect the accuracy and reliability of temperature detection instrumentation.

Functions of Temperature Detectors

Although the temperatures that are monitored vary slightly depending on the details of facility design, temperature detectors are used to provide three basic functions: indication, alarm, and control. The temperatures monitored may normally be displayed in a central location, such as a control room, and may have audible and visual alarms associated with them when specified preset limits are exceeded. These temperatures may have control functions associated with them so that equipment is started or stopped to support a given temperature condition or so that a protective action occurs.

Detector Problems

In the event that key temperature sensing instruments become inoperative, there are several alternate methods that may be used. Some applications utilize installed spare temperature detectors or dual-element RTDs. The dual-element RTD has two sensing elements of which only one is normally connected. If the operating element becomes faulty, the second element may be used to provide temperature indication. If an installed spare is not utilized, a contact pyrometer (portable thermocouple) may be used to obtain temperature readings on those pieces of equipment or systems that are accessible.

If the malfunction is in the circuitry and the detector itself is still functional, it may be possible to obtain temperatures by connecting an external bridge circuit to the detector. Resistance readings may then be taken and a corresponding temperature obtained from the detector calibration curves.

Environmental Concerns

Ambient temperature variations will affect the accuracy and reliability of temperature detection instrumentation. Variations in ambient temperature can directly affect the resistance of components in a bridge circuit and the resistance of the reference junction for a thermocouple. In addition, ambient temperature variations can affect the calibration of electric/electronic equipment. The effects of temperature variations are reduced by the design of the circuitry and by maintaining the temperature detection instrumentation in the proper environment.

The presence of humidity will also affect most electrical equipment, especially electronic equipment. High humidity causes moisture to collect on the equipment. This moisture can cause short circuits, grounds, and corrosion, which, in turn, may damage components. The effects due to humidity are controlled by maintaining the equipment in the proper environment.

Summary

Detector Uses Summary

- Temperature detectors are used for:
  - Indication
  - Alarm functions
  - Control functions
- If a temperature detector became inoperative:
  - A spare detector may be used (if installed)
  - A contact pyrometer can be used
- Environmental concerns:
  - Ambient temperature
  - Humidity

TEMPERATURE DETECTION CIRCUITRY

The bridge circuit is used whenever extremely accurate resistance measurements are required (such as RTD measurements).

EO 1.9 Given a simplified schematic diagram of a basic bridge circuit, STATE the purpose of the following components:

a. R_1 and R_2
b. R_x
c. Adjustable resistor
d. Sensitive ammeter

EO 1.10 DESCRIBE the bridge circuit conditions that create a balanced bridge.

EO 1.11 Given a block diagram of a basic temperature instrument detection and control system, STATE the purpose of the following blocks:

a. RTD
b. Bridge circuit
c. DC-AC converter
d. Amplifier
e. Balancing motor/mechanical linkage

EO 1.12 DESCRIBE the temperature instrument indication(s) for the following circuit faults:

a. Short circuit
b. Open circuit

EO 1.13 EXPLAIN the three methods of bridge circuit compensation for changes in ambient temperature.

Bridge Circuit Construction

Figure 8 shows a basic bridge circuit which consists of three known resistances, R_1, R_2, and R_3 (variable), an unknown variable resistor R_X (RTD), a source of voltage, and a sensitive ammeter.

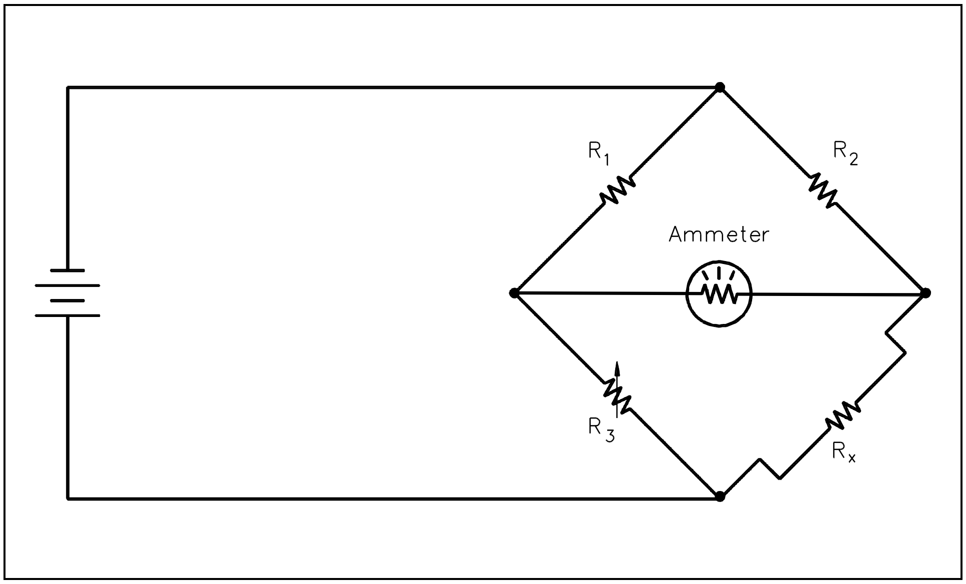

Figure 8 Bridge Circuit

Resistors R_1 and R_2 are the ratio arms of the bridge. They ratio the two variable resistances for current flow through the ammeter. R_3 is a variable resistor known as the standard arm that is adjusted to match the unknown resistor. The sensing ammeter visually displays the current that is flowing through the bridge circuit. Analysis of the circuit shows that when R_3 is adjusted so that the ammeter reads zero current, the resistance of both arms of the bridge circuit is the same. Equation 1-1 shows the relationship of the resistance between the two arms of the bridge.

$$\frac{R_1}{R_3} = \frac{R_2}{R_x} \qquad (1\text{-}1)$$

Since the values of R_1, R_2, and R_3 are known values, the only unkown is R_x. The value of R_x can be calulated for the bridge during an ammeter zero current condition. Knowing this resistance value provides a baseline point for calibration of the instrument attached to the bridge circuit. The unknown resistance, R_x, is given by Equation 1-2.

$$R_x = \frac{R_2 R_3}{R_1} \qquad (1\text{-}2)$$

Bridge Circuit Operation

The bridge operates by placing R_x in the circuit, as shown in Figure 8, and then adjusting R_3 so that all current flows through the arms of the bridge circuit. When this condition exists, there is no current flow through the ammeter, and the bridge is said to be balanced. When the bridge is balanced, the currents through each of the arms are exactly proportional. They are equal if $R_1 = R_2$. Most of the time the bridge is constructed so that $R_1 = R_2$. When this is the case, and the bridge is balanced, then the resistance of R_x is the same as R_3, or $R_x = R_3$.

When balance exists, R_3 will be equal to the unknown resistance, even if the voltage source is unstable or is not accurately known. A typical Wheatstone bridge has several dials used to vary the resistance. Once the bridge is balanced, the dials can be read to find the value of R_3. Bridge circuits can be used to measure resistance to tenths or even hundredths of a percent accuracy. When used to measure temperature, some Wheatstone bridges with precision resistors are accurate to about + 0.1°F.

Two types of bridge circuits (unbalanced and balanced) are utilized in resistance thermometer temperature detection circuits. The unbalanced bridge circuit (Figure 9) uses a millivoltmeter that is calibrated in units of temperature that correspond to the RTD resistance.

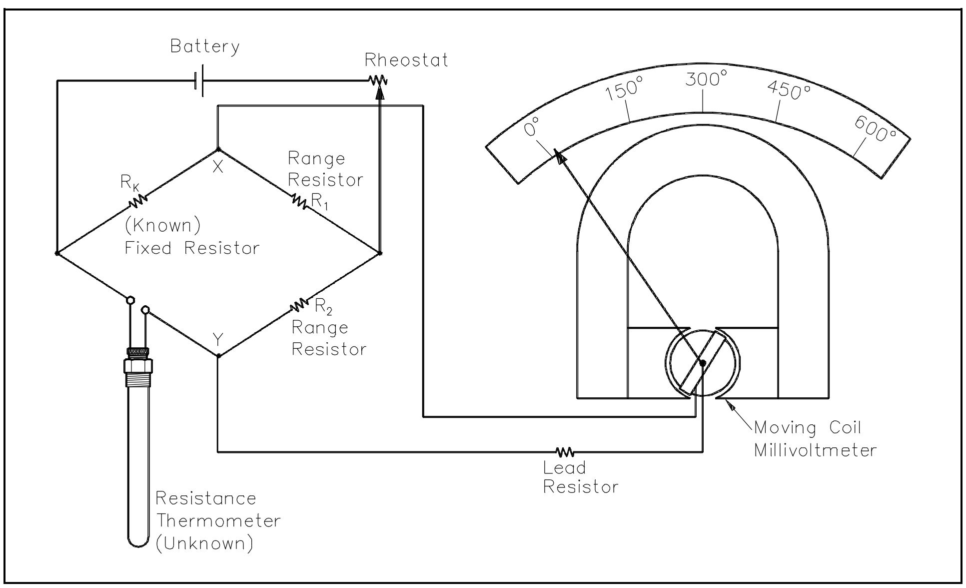

Figure 9 Unbalanced Bridge Circuit

The battery is connected to two opposite points of the bridge circuit. The millivoltmeter is connected to the two remaining points. The rheostat regulates bridge current. The regulated current is divided between the branch with the fixed resistor and range resistor R_1, and the branch with the RTD and range resistor R_2. As the electrical resistance of the RTD changes, the voltage at points X and Y changes. The millivoltmeter detects the change in voltage caused by unequal division of current in the two branches. The meter can be calibrated in units of temperature because the only changing resistance value is that of the RTD.

The balanced bridge circuit (Figure 10) uses a galvanometer to compare the RTD resistance with that of a fixed resistor. The galvanometer uses a pointer that deflects on either side of zero when the resistance of the arms is not equal. The resistance of the slide wire is adjusted until the galvanometer indicates zero. The value of the slide resistance is then used to determine the temperature of the system being monitored.

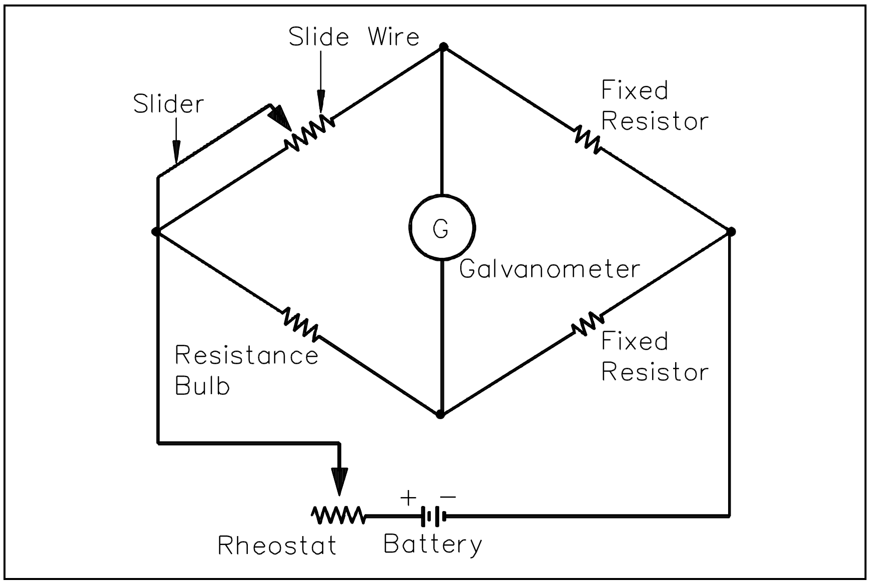

Figure 10 Balanced Bridge Circuit

A slidewire resistor is used to balance the arms of the bridge. The circuit will be in balance whenever the value of the slidewire resistance is such that no current flows through the galvanometer. For each temperature change, there is a new value; therefore, the slider must be moved to a new position to balance the circuit.

Temperature Detection Circuit

Figure 11 is a block diagram of a typical temperature detection circuit. This represents a balanced bridge temperature detection circuit that has been modified to eliminate the galvanometer.

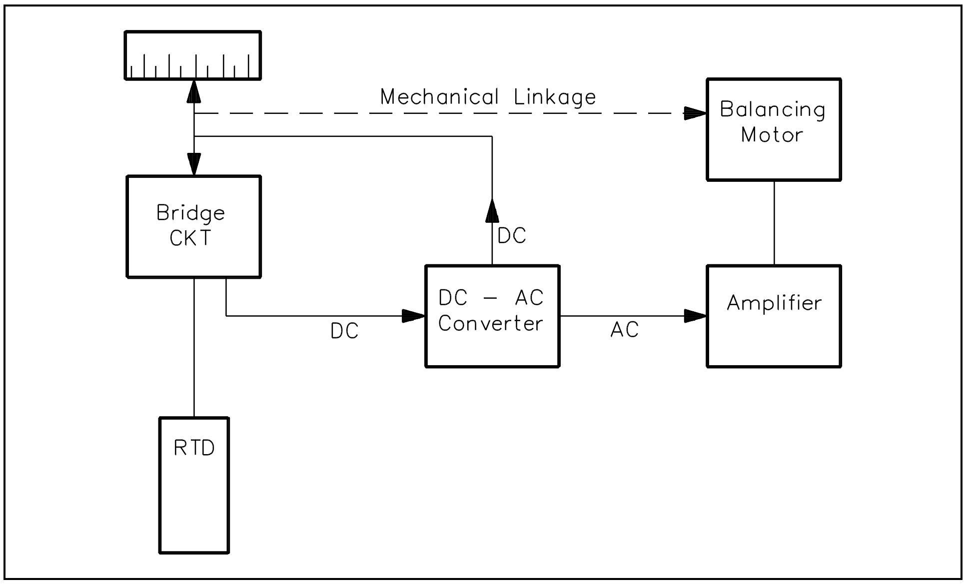

Figure 11 Block Diagram of a Typical Temperature Detection Circuit

The block consists of a temperature detector (RTD) that measures the temperature. The detector is felt as resistance to the bridge network. The bridge network converts this resistance to a DC voltage signal.

An electronic instrument has been developed in which the DC voltage of the potentiometer, or the bridge, is converted to an AC voltage. The AC voltage is then amplified to a higher (usable) voltage that is used to drive a bi-directional motor. The bi-directional motor positions the slider on the slidewire to balance the circuit resistance.

If the RTD becomes open in either the unbalanced and balanced bridge circuits, the resistance will be infinite, and the meter will indicate a very high temperature. If it becomes shorted, resistance will be zero, and the meter will indicate a very low temperature.

When calibrating the circuit, a precision resistor of known value is substituted for the resistance bulb, as shown in Figure 12.

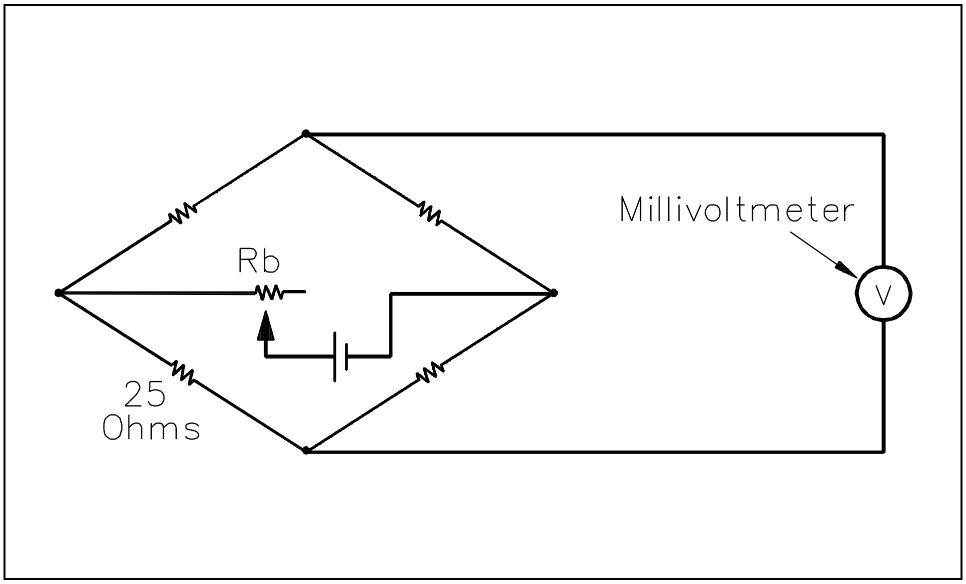

Figure 12 Resistance Thermometer Circuit with Precision Resistor in Place of Resistance Bulb

Battery voltage is then adjusted by varying R_b until the meter indication is correct for the known resistance.

Temperature Compensation

Because of changes in ambient temperature, the resistance thermometer circuitry must be compensated. The resistors that are used in the measuring circuitry are selected so that their resistance will remain constant over the range of temperature expected. Temperature compensation is also accomplished through the design of the electronic circuitry to compensate for ambient changes in the equipment cabinet. It is also possible for the resistance of the detector leads to change due to a change in ambient temperature. To compensate for this change, three and four wire RTD circuits are used. In this way, the same amount of lead wire is used in both branches of the bridge circuit, and the change in resistance will be felt on both branches, negating the effects of the change in temperature.

Summary

Temperature detection circuit operation is summarized below.

Circuit Operation Summary

- The basic bridge circuit consists of:
  - Two known resistors (R_1 and R_2) that are used for ratioing the adjustable and known resistances
  - One known variable resistor (R_3) that is used to match the unknown variable resistor
  - One unknown resistor (R_x) that is used to measure temperature
  - A sensing ammeter that indicates the current flow through the bridge circuit
- The bridge circuit is considered balanced when the sensing ammeter reads zero current.
- A basic temperature instrument is comprised of:
  - An RTD for measuring the temperature
  - A bridge network for converting resistance to voltage
  - A DC to AC voltage converter to supply an amplifiable AC signal to the amplifier
  - An AC signal amplifier to amplify the AC signal to a usable level
  - A balancing motor/mechanical linkage assembly to balance the circuit's resistance
- An open circuit in a temperature instrument is indicated by a very high temperature. A short circuit in a temperature instrument is indicated by a very low temperature.
- Temperature instrument ambient temperature compensation is accomplished by:
  - Measuring circuit resistor selection
  - Electronic circuitry design
  - Use of three or four wire RTD circuits