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Resistance Temperature Detector (RTD) System in Nuclear Power Plant (A Short Review)

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RESISTANCETEMPERATUREDETECTORRTDSYSTEMINNUCLEARPOWERPLANTASHORTREVIEW

Strictly as per the compliance and regulations of:

Resistance Temperature Detector (RTD) System in Nuclear Power Plant (A Short Review)

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Keywords: instrumentation and control, resistance temperature detector, probabilistic risk assessment, advance reactor concept, generation IV, light water reactor, supercritical water reactor, pressurized heavy water reactor, sodium fast reactor, and molten salt reactor.

I. Introduction

Temperature-type sensors are presently operating in many types of reactors of the water type, and they are in the form of either Resistance Temperature Detectors (RTDs) or Thermocouples (TC) inside a Stainless Steel (SS) tube sheath.

The Resistance Temperature Detector, or RTD, is a sensor whose resistance changes with temperature. The RTD, which is typically made of platinum (Pt) wire wrapped around a ceramic bobbin, has a physical property behavior that is more accurate and linear over a wider temperature range than a thermocouple.

RTDs have sensing elements, which are made of metal, typically platinum (Pt). The platinum metal in some RTDs is in the form of a wire wrapped around a mandrel (typically magnesium oxide) inside a stainless-steel tube with a magnesium oxide insulator between the mandrel and the inner wall of the sheath, as illustrated in Figure 1. [1]

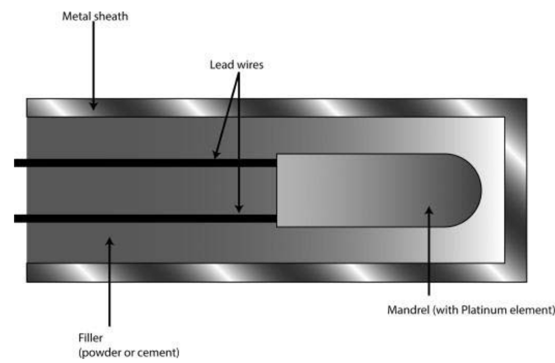

Figure 1: Resistance Temperature Detector [1]

Another different manufactured and designed type of RTD uses a platinum wire coil cemented to the interior wall of a hollow section of a metallic tube, as illustrated in Figure 2. [1]

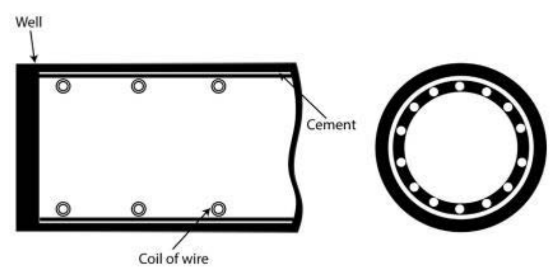

Figure 2: A Fast Response Resistance Temperature Detector [1]

This approach provides a very fast response to temperature measurement because the heat transfer resistance between the coil and the sheath is small.

Due to the thermal conductivity behavior of platinum (Pt), with a well-defined temperature resistance relationship, the built-in instrumentation of this kind of RTD measures the resistance and converts it to a temperature measurement using temperature versus the resistance calibration data. The resistance increases with temperature, and the temperature-resistance

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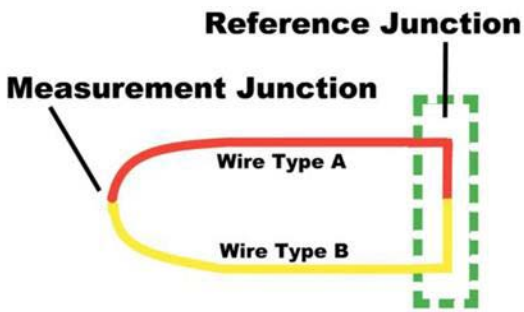
relation is almost linear. But the readout instrumentation accounts for the small non-linearity.

However, in the case of thermocouple (TC) type instrumentation, it comes with the implementation of two different types of dissimilar wires that are joined to form the thermocouple junction, as illustrated in Figure 3.



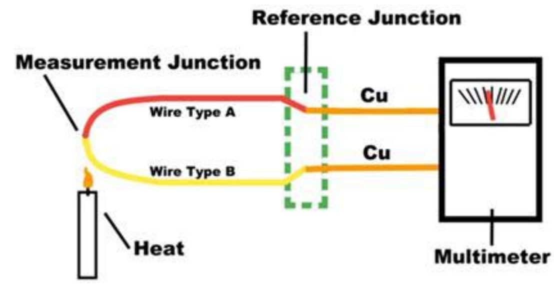
(Source: Courtesy of Enercorp)

Figure 3: Basic Thermocouple Concept

A thermocouple measures temperature, so technically, a thermocouple is a type of thermometer. Of course, not all thermometers are the same. Two different metals make up a thermocouple. Generally, it takes the form of two wires twisted, welded, or crimped together. Temperature is sensed by measuring the voltage. Heating a metal wire will cause the electrons within the wire to get excited and want to move. We can measure this potential for electrons to move with a multimeter. With this measurement, we can calculate the temperature.

In short, a thermocouple translates temperature energy into an electrical signal. This signal can be acted upon, perhaps directly by a person who is monitoring the thermocouple, but more likely by an automated system that observes, records, or uses the data to perform an action. Let us take a look at a diagram of a thermocouple to get an idea of how this instrument works.

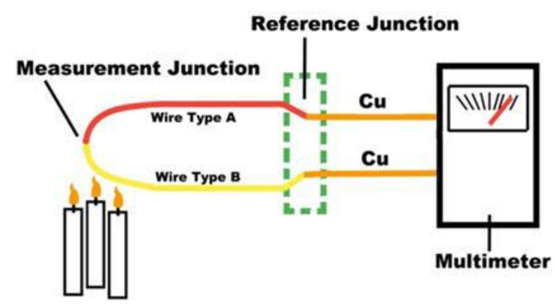
As one can see in Figure 3, a thermocouple is a relatively simple instrument. Two wires comprised of dissimilar metals are connected where the temperature needs to be measured. This connection is called the measurement junction. The other ends of the wires are also connected. but this time in an area where the temperature is known. This area is called the reference junction. Let us do a small experiment by heating one end of the thermocouple and adding a way to measure what happens. See Figure-4



(Source: Courtesy of Enercorp)

Figure 4: Heating a Thermocouple

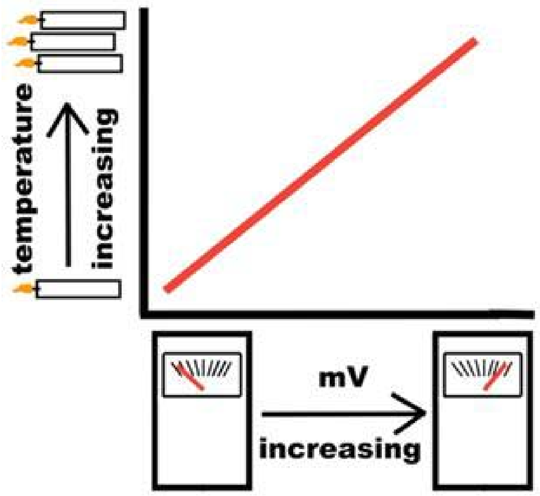
By applying heat to the measurement junction, we can cause electrons in the metal wire to excite and flow, producing a current. Since we are looking to measure the voltage of this current, we have connected the reference junction to a multimeter with copper wire. The current sensed by our multimeter gives us a reading in millivolts (mV). Let us increase the temperature at our measurement junction and see what happens to the reading on our multimeter. See Figure-5.



(Source: Courtesy of Enercorp)

Figure 5: Applying More Heat

As the measurement junction heats up more, the reading on our multimeter at the reference junction will increase correspondingly. The important part about the value of our multimeter is that it is a function of the difference in temperature between the two junctions. We can chart the relationship between the two variables. Thus, if we know the temperature of the controlled reference junction and can measure the voltage change as the measurement junction is heated, then, we can determine the temperature at the measurement junction. See Figure-6



(Source: Courtesy of Enercorp)

Figure 6: Charting Temperature vs. Voltage

Although a thermocouple does not directly tell us the temperature of the measurement junction, it does give us a voltage. This voltage is a readable electrical signal that is dependent on the difference in temperature between the measurement and reference junctions. You can graph or table this correlation between voltage and temperature. And we can reference the voltage signal to determine the associated temperature. Some aspects, like the type of wires used and the temperature of the reference junction, must remain constant. But ultimately, we have a repeatable process to measure temperature, one that is infinitely replicable.

Moreover, keep in mind that a thermocouple creates a voltage that depends on the temperature difference.

Between the junction and open end of the wires. So, a thermocouple voltage is a function of the temperature difference between the open end and the junction. The junction temperature is obtained as follows:

- ✓ Instrumentation measures the thermocouple voltage.
- ✓ Instrumentation measures the open-end temperature using a different type of sensor (usually a thermistor or integrated circuit sensor operating at the instrumentation which operates at ambient temperature).
- ✓ –Instrumentation calculates the voltage that would occur for a thermocouple with a junction at the ambient temperature measured at the instrumentation and the open end at 0^0C.
- ✓ –Instrumentation adds the measured thermocouple junction-to-open end voltage and the calculated ambient-to 0^0C voltage.
- ✓ Instrumentation uses the summed voltages to calculate junction temperature using standard calibration data for a thermocouple with the open end at 0^0C.

Thermocouples may be used for in-core coolant temperature measurements. Type-K thermocouples (Chromel - Alumel) or type-N (Nicrosil - Nisil) are suitable. Type-N is usually preferred for high temperature measurements because of a de-calibration tendency in Type-K. Thermocouples may have the junction insulated from the sheath or have the thermocouple wires attached to the sheath as illustrated in Figure-7 [1] (a grounded junction thermocouple). Grounded-junction thermocouples have faster time response than insulated junction thermocouples. [1]

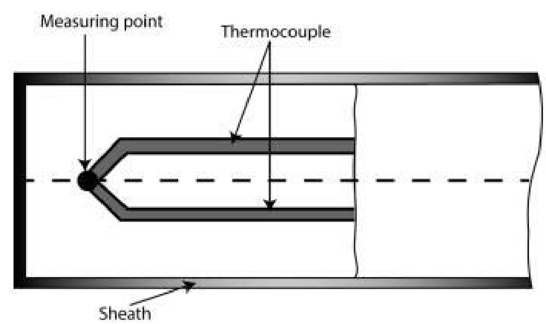


Figure 7: A Sheathed Thermo-Couple Configuration [1]

In summary, thermocouples are commonly used for measuring higher temperatures and larger temperature ranges.

To summarize how thermocouples work, any conductor subjected to a thermal gradient will generate a small voltage. This phenomenon is known as the *Seebeck effect*. The magnitude of the generated voltage is dependent on the type of metal. Practical applications of the Seebeck effect involve two dissimilar metals that are joined at one end and separated at the other end. The junction's temperature can be determined via the voltage between the wires at the non-junction end.

There are various types of thermocouples. Certain combinations of alloys have become popular, and the desired combination is driven by variables including cost, availability, chemical properties, and stability. Different types are best suited for different applications, and they are commonly chosen based on the required temperature range and sensitivity. Figure-8 shows a graph of thermocouple characteristics.

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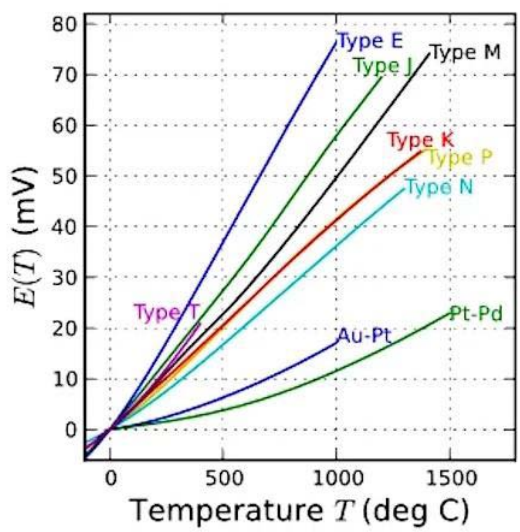


(Source: Courtesy of wikipedia.org)

Figure 8: Thermocouple Characteristics

"Dynamics and Control of Nuclear Reactors" presents the most recent knowledge and research in the new generation of reactor dynamics (i.e., Advanced Reactor Concepts (ARC)), where instrumentation and control (I&C) play an important role in ensuring the safe and economic operation of nuclear power plants.

The dynamic characteristics can be sensible in the family of Light Water Reactors (LWRs) such as Pressurized Water Reactors (PWRs), Boiling Water Reactors (BWRs), Supercritical Water Reactor (Super-Critical Water-cooled Reactors (SCWRs), Pressurized Heavy Water Reactors (PHWRs) and Molten Salt Reactors (MSRs). It also provides pertinent, but less detailed information on Small Modular Reactors (SMRs), such as Sodium Fast Reactors (SFRs), and Gas-Cooled Reactors (GCRs).

II. The Basics of a Resistance Temperature Detector (RTD)

Resistance Temperature Detector (RTD) operate on the principle that the electrical resistance of a metal changes predictably in a linear and repeatable manner with changes in temperature. The traditional RTD element is constructed of a small coil of platinum, copper, or nickel wire wound to a precise resistance value around a ceramic or glass bobbin. The winding is generally of the helix style for industrial use.

The most common RTD element material is platinum, as it is a more accurate, reliable, chemically resistant, and stable material, making it less susceptible to environmental contamination and corrosion than other metals. It is also easy to manufacture and widely standardized, with readily available platinum wire available in very pure form with excellent reproducibility of its electrical characteristics. Platinum also has a higher melting point, giving it a wider operating temperature range.

"For an RTD sensor, it is the wires, which connect to the sensing element, and the wire insulation, which generally limit the maximum application temperature of the sensor." Measuring the temperature requires accurate resistance measurement. To measure the resistance, it is necessary to convert the resistance to a voltage and use the voltage to drive a differential input amplifier. "The use of a differential input amplifier is important as it will reject the common mode noise on the leads of the RTD and provide the greatest voltage sensitivity." [2]

The RTD signal is typically measured by connecting the RTD element to one leg of a Wheatstone bridge, either excitable by a constant reference voltage or in series with a precision current reference, and measuring the corresponding Intensity Resistance (IR) voltage drop. The latter method is generally preferred as it has less dependence on the reference resistance of the RTD element.

Furthermore, temperature is one of the most routinely measured physical quantities in industry, in particular in the core of nuclear water reactors while they are in operation mode, and the safety of their operation period is very important from a control room perspective. Other industries, for instance, food and beverage manufacturers, must maintain certain temperature conditions to ensure that their products are in compliance with Food and Drug Administration (FDA) regulations and to prevent spoilage. The chemical industry must carefully monitor temperature to control reaction kinetics, prevent runaway reactions and side reactions, and optimize energy usage. Companies such as Control Automation are providing a lot of commercialization of this device to so many industries that are in need of such instrumentation, and it can also be scaled up to meet the needs of the nuclear industries as well.

As we have stated above, there are many ways to measure temperature, most of which take advantage of hotter atoms that have more energy and thus vibrate quicker. Thermal expansion methods of temperature detection, such as the expansion of mercury (or colored alcohol) in a thermometer, are evidence of this faster vibration.

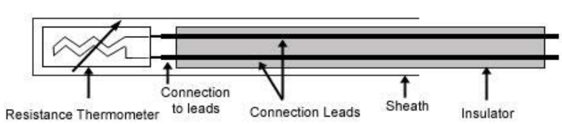
The electrical response of materials changes with temperature as well. If two dissimilar metals are in contact, they will generate a voltage called the Seebeck voltage. The Seebeck voltage will vary linearly with temperature. Thermocouples measure temperature based on this effect.

As a material heats up, its electrical resistance increases. The atoms in the material vibrate faster, and thus, flowing electrons are more likely to be repulsed by existing electrons trapped in the orbits of these atoms. As anyone shooting a basketball knows, it is easier to shoot the basket if the defender is not flailing their arms in the way; the same is true with an electron trying to pass through a material. If the temperature were to drop to absolute zero (no atomic motion), the resistance would be very low, as the electrons would not encounter the random motion of these atoms and could zip through easily. See Figure 9, where the RTD is inside these metal housings.

(Image used courtesy of El-Sensor)

Figure 9: Several Commercial RTD Probes

A RTD is simply a piece of metal wire, usually platinum (Pt), with a known resistance characteristic at zero degrees Celsius, as shown in Figure 10.



(Image used courtesy of Psanderson)

Figure 10: Diagram of a Resistance Temperature Detector (RTD)

It also must have a predictable resistance with a change in temperature. This change in resistance is described by a linear equation. For example, one of the most common RTDs on the market is the "Pt100," which stands for a platinum wire with 100 Ω of resistance at 0 ^{0}C. This RTD can also be described by the equation:

$$R = (0.385\ \Omega\ ^0C)\ T + 100\ \Omega$$

Where R is the resistance and T is the temperature. Solving for T:

$$T = (2.597\ \Omega\ ^0C)\ R - 259.7\ ^0C$$

Note that: The type of Platinum RTD is often indicated with the abbreviation "Pt" followed by a number, e.g., "Pt100". The number indicates the Platinum resistance at 0 ^{0}C. The Temperature Coefficient of Resistance (TCR) of the most common platinum RTD is 0.00385/(0C). The TCR indicates the average resistance change per zero Celsius and can be seen as a sensitivity parameter. In other words, the resistance of the most common platinum RTD changes by 0.38% per 0C [3].

While the resistance change can be measured with a multimeter, a much more common way to measure a resistance change is to use a “Wheatstone Bridge” circuit. A constant-voltage bridge circuit similar to that used with strain gauges is usually used for sensing the resistance change that occurs. Figure-11 shows a Wheatstone Bridge for reference. The RTD acts as an adjustable resistor and thus could replace Rx. As the resistance changes, the voltage measured across “null” will also change.

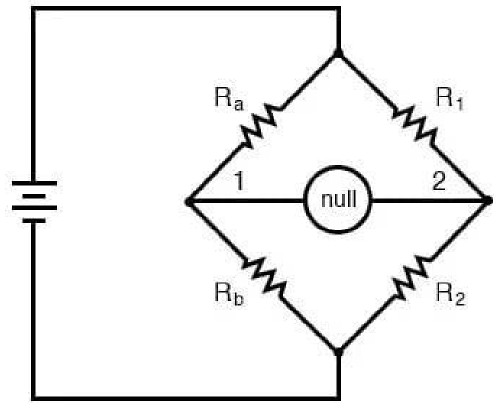


Figure 11: Wheatstone Bridge

One could use their knowledge of circuit analysis and the linear equation for the RTD to calculate the temperature change for a given voltage change. A more common way to determine the temperature is through a calibration procedure.

III. Resistance Temperature Detector (RTD) Calibration

Place an RTD in an ice water bath to calibrate it. When the voltage stops changing, take note of the temperature (measured with a calibrated thermometer) and voltage at the Wheatstone Bridge circuit, as shown in FIGURE 12. Repeat this process with room-temperature water, heated water, boiling water, etc. The more data points, the better. From there, one can plot these points and find a best-fit line that will describe the relationship between voltage and temperature.

Figure 12: A Way to Calibrate an RTD

The calibration procedure will take some time to perform. However, one of the big advantages of calibration is that it automatically accounts for the temperature change on the nearby wiring, as its resistance is changing, just like the RTD's resistance is changing.

IV. Advantages and Limitations of Resistance Temperature Detectors (RTDs)

RTDs can provide an accurate temperature measurement, provided the temperature does not change rapidly. Therefore, they can be used for repeatable, steady-state reactions and processes.

As we stated before, RTDs are slower to respond than other temperature sensors. In order to understand why, consider that there are three modes of heat transfer: conduction, convection, and radiation.

Conduction requires a temperature difference to flow heat directly between two solid materials, such as touching a hot stove. Convection is heating transfer due to moving fluid, such as blowing on hot soup. Radiative heat transfer deals with which wavelengths and at what intensity are emitted from an object, such as feeling the heat from an open fire.

The RTD does not directly touch the heated environment, and so conduction is limited. RTDs are often housed in an evacuated chamber, limiting convection. Radiative heat transfer is possible, though it is much more efficient at high temperatures. Therefore, all three methods of heat transfer are much slower in an RTD.

Another consideration is the resistance of the lead wires that connect the RTD to your measurement. The resistance of these leads will increase with temperature as well. If the leads are replaced with longer ones, the resistance will increase and make up a larger percentage of the total resistance.

There are several ways to overcome the problems presented by the lead wires. In general, keep lead wires short and calibrate and spot-check the RTD whenever possible. If the system is calibrated with the RTD leads, it will account for the resistance of the leads at specific temperatures. Also, RTDs can be plugged into wireless transmitters for data logging instead of running longer leads.

RTDs are just one method of measuring temperature. They are particularly useful when temperatures need to be accurately measured and recorded but aren't expected to change very quickly.

V. Resistance Temperature Detectors for Advanced Reactors

It is well known that the response time of RTDs and thermocouples is subject to change over time.

Many factors contribute to this degradation; for example, vibration can cause RTDs and thermocouples to move out of their thermowells and result in an increase in response time. Temperature variations can also result in changes in sensor response time. For example, inherent voids in sensor insulation materials can expand or contract and cause the response time to change. For these and other reasons, the response time of RTDs and thermocouples is measured periodically in nuclear power plants (see Figure 13) [4].

The harsh environments of advanced reactors, such as high temperatures, high levels of nuclear radiation, the potential for corrosion, and limited access to sensors for maintenance, are just a few examples of instrumentation challenges that must be designed, developed, and qualified for advanced reactors. [5]

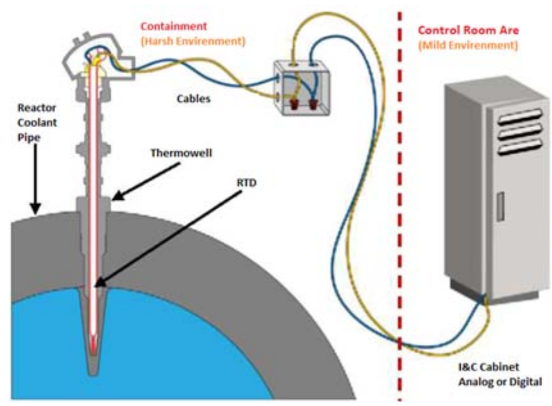


Figure 13: Illustration of Temperature Sensor System and Connections in a Nuclear Power Plant

Furthermore, the operating cycles of most advanced reactors are expected to be much longer than those of conventional plants, adding to the need for instrumentation that can maintain calibration and response time over extended intervals. [5]

Advanced reactors, with respect to their operating characteristics, can have high core outlet temperatures, unique primary coolants, significantly longer refueling intervals, and complex geometries that complicate the deployment of conventional Instrumentation and Control (I&C) sensors.

For example, Sodium, unlike water, is a non-moderating coolant and thus allows for a fast neutron spectrum. A shorter neutron lifetime and magnitude of delay coefficient result in a reactor that is dynamically more sensitive than a conventional pressurized water reactor (PWR). Thus, I&C sensors in sodium-cooled reactors must be designed for reliable operation at high temperatures > 500 oC), have a fast response in order to maintain stable reactor control and timely shutdown, and provide diagnostic capability in case of inadvertent reactivity addition or equipment problems. [5]

RTDs have a long operating history in conventional PWRs, and their failure modes and degradation mechanisms are well understood. However, they were not designed to withstand prolonged exposure to elevated temperatures, high radiation, and the corrosive coolants expected in the primary systems of advanced reactors. as well as frequent conventional RTD maintenance or replacement to combat increased calibration drift or premature response time degradation is not practical for advanced reactors with extended operating cycles. Therefore, new I&C sensors must be developed and qualified for service in advanced reactor environments.

VI. Conclusion

As we stated in the abstract of this short review article, the Resistance Temperature Detector (RTD) element does not respond instantaneously to changes in water temperature, but rather there is a time delay before the element senses the temperature change, and in nuclear reactors this delay must be factored into the computation of safety setpoints. For this reason, it is necessary to have an accurate description of the RTD timing response. This Safety Evaluation (SE) is a review of the current state of the art of engineers concerns and research by describing and measuring this time response that is not real-time but at least near real-time.

Historically, the RTD time response has been characterized by a single parameter called the Plunge time constant, or simply the Plunge T. The Plunge T is defined as the time required for the RTD to achieve 63.2% of its final response after a step temperature change is impressed on the surface of the RTD. Such a temperature change can be achieved by plunging the RTD into a heat sink, such as water, oil, ·sand, or molten metal. When T is measured by this means, the technique is called the plunge test method. For more information, refer to this references the U.S. NRC. [6]

However, bear in mind that the time response is not only a function of the RTD itself but also depends on the properties of the thermowell and the thermal characteristics of the medium in which the thermowell or RTD is immersed.

The thermal properties of all these components change with temperature, and the heat transfer properties of the medium (water) change with flow velocity.

The match between the RTD and the thermowell affects the time response, and even the slight change in match that occurs when an RTD is removed from a thermowell and placed back in the same well can significantly change the time response. Thus, it is important to simulate service conditions as closely-as possible, when testing the RTD time response.

Furthermore, there are a variety of Resistance Temperature Detectors (RTDs) sensors that are specially designed to ensure precise and repeatable temperature measurements of media such as water in the reactor core.

Many companies in this industry and RTD manufacturing build sensors to meet the most demanding industrial applications while providing customers with a lower total cost of ownership.

As it is, these detectors are frequently used in many industries. Care must be taken to eliminate moisture, and vibration effects can be troublesome as well. Companies like Thermo Sensors Corporation provide the utmost in the current state of the art in materials, techniques, and research, and this RTD features lifetime moisture free as well as excellent vibration resistance.

Bottom line, Resistive Temperature Detectors, also known as Resistance Thermometers, are perhaps the simplest temperature sensors to understand. RTDs are similar to thermistors in that their resistance changes with temperature.

However, rather than using a special material that is sensitive to temperature changes—as with a thermistor—RTDs use a coil of wire wrapped around a core made from ceramic or glass.

The RTD wire is made of pure material, typically platinum, nickel, or copper, and the material has an accurate resistance–temperature relationship that is used to determine the measured temperature.

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