Fundamental Thermometry for Long-Term and High-Temperature Deployment in Generation IV Reactors

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Abstract

Generation IV (GenIV) reactors have significantly more technically challenging temperature measurement requirements in terms of sustained higher temperature operation and decreased calibration opportunities than current-generation nuclear power plants (NPPs). The more demanding survival requirements place a premium on nondrifting, long-term reliable instrumentation. Both Johnson noise thermometry (JNT) and radiation thermometry (RT) can be implemented in fundamental, nondrifting forms. However, both techniques must overcome significant technical challenges to be adequately reliable for employment as primary measurements in NPPs. RT relies upon both invariance in the optical path between the measured surface and the condition of that surface to remain "ab initio." Johnson noise is a small signal, wide-band phenomenon that must be distinguished from competing mechanical vibrations and external electromagnetic noises, both of which are plentiful in NPP environments. This paper provides an overview and analysis of possible RT and JNT applications to GenIV reactors.

1. Introduction

All of the candidate Generation IV nuclear power plants (NPPs) operate at significantly higher temperatures than current-generation light-water reactors, resulting in more rapid deterioration of the temperature transducers. Further, the less frequent refueling outages of GenIV plants decrease the thermometer calibration opportunities as compared to current-generation NPPs. The requirement for high-accuracy measurement combined with the inevitable drift in the material properties of temperature transducers results in high value being placed on temperature measurements that depend on invariant, fundamental phenomena. Two widely recognized temperature measurement techniques rely directly on fundamental, invariant phenomena. Radiation thermometry (RT) is based upon the variation of the emission of light from a surface with changes in its temperature. The origin of this surface radiance is the acceleration (oscillation) of the electrical charges within the material. Johnson noise thermometry (JNT), correspondingly, is based on electrically measuring the random vibrations of the charges in a resistor. Because temperature is defined as the mean translational kinetic energy of an atomic ensemble, both measurement techniques are, in pure form, fundamental and non-drifting.

Daunting technical challenges must be overcome to apply either of these techniques to GenIV reactors. Both techniques rely upon precision measurement electronics that must be implemented in a NPP compatible form (possibly with safety-grade reliability). Further, RT relies upon both invariance in the optical path between the measured surface and the condition of that surface. Consequently, both must be controlled between recalibrations for successful fundamental RT implementation. Johnson noise is a small-signal, wide-band phenomenon, which must be distinguished from competing mechanical vibrations and external electromagnetic noises, both of which are plentiful in NPP environments. In addition, the capacitance of the signal cable between the resistive element and measurement electronics and the input electronic circuitry itself spectrally distorts the Johnson noise, which limits the allowable separation between the delicate measurement electronics and the reactor.

2. Background

2.1 Radiation thermometry

RT relies upon the variation of temperature-induced light emission from a surface with changes in its temperature. The origin of this surface radiance is the acceleration (vibration) of the atoms within the material. Conservation of momentum dictates that anytime a particle undergoes acceleration, such as the continuous changes in direction of electrons as they orbit nuclei, it must emit a particle with equal and opposing momentum. In the case of nuclei and electrons vibrating with temperature, photons are the emitted particles. This emission inherently takes place continuously from all materials. As acceleration of the electrons and nuclei within materials is a direct consequence of temperature, the amount of light generated varies directly with temperature. The increasing magnitude of acceleration with increasing temperature results in both more emitted photons and larger energies on average for those photons. Neighboring atoms in opaque materials efficiently reabsorb the photons emitted by internal atoms. However, externally directed photons with origins near the surface can escape a material. The probability that thermally emitted photons will escape a material's surface is referred to as its emissivity. The emissivity of a material is dependent on its physical and chemical properties, so while the origins of thermally emitted light are fundamental and material independent, the actual character of the emitted light from a surface is not. This means that some implementations of RT are not fundamental and are vulnerable to material property shifts.

To overcome material surface condition dependence of RT, another property of surface emission is exploited. Conservation of energy dictates that an interior photon approaching a material's surface must be emitted, reflected, or absorbed. The same is true for externally located photons impinging on a surface. Also, to be at constant temperature, another photon must be emitted for each one absorbed, thus effectively restricting the surface photon interaction options to emission or reflection. All materials have some probability of emission and some of reflection. For example, shiny metals have high reflectivity and correspondingly low emissivity. Consider a lacuna entirely contained within a material. Every photon emitted from the lacuna's enveloping surface is matched by one absorbed, establishing a constant temperature electromagnetic equilibrium. Due to the practically infinite number of emissions and reflections involved in creating the electromagnetic equilibrium, the particular value of the material's emission and reflection coefficients does not alter the character of the equilibrium. Even for a near perfect mirror material, photons would be absorbed and re-emitted many times per second. This phenomenon can be exploited to produce a quasi-fundamental temperature measurement by arranging a material's surface such that any emitted photon must undergo multiple emissions and reflections before finally escaping the material. Conceptually this resembles poking a pinhole in a shallowly buried lacuna in a material. The characteristics of the emerging light from such an arrangement are essentially independent of the characteristics of the material or its surface, resulting in a quasi-fundamental representation of temperature. This arrangement is referred to as a blackbody emitter because the emitted light characteristics are those for an ideal material with an emissivity of one.

The amount and wavelength of radiation emitted (spectral radiance) by a blackbody was first derived by Planck from quantum mechanics—

$$L_b(\lambda, T) = \frac{2hc^2}{\lambda^5\left(e^{\frac{hc}{\lambda k_B T}} - 1\right)}, \qquad (1)$$

where h is Planck's constant, k_B is Boltzmann's constant, T is absolute temperature, c is the speed of light in a vacuum, λ represents wavelength, and the subscript b on L denotes blackbody conditions. Plank's Law illustrates several key points about thermal radiation. For all wavelengths, the amount of radiation emitted increases with temperature. As temperature increases, relatively more radiation is emitted at progressively shorter wavelengths.

2.2 Johnson Noise Thermometry

JNT is also based on measuring the temperature defining random vibrations of atomic ensemble within a material. Temperature causes the charges (electrons and nuclei) within a material to move. This motion results in a random, zero mean noise voltage across any electrically resistive material whose amplitude varies directly with temperature. The Nyquist equation describes the voltage produced by the vibration of the electrons within a resistor at a given temperature, thus providing a mathematical relationship between temperature, resistance, and voltage generated. For frequencies below a few gigahertz, the relationship between the absolute temperature of a resistor (*T*), its resistance (*R*), the frequency band of measurement (*Δf*), and the measured mean-square noise voltage is

$$\overline{V^2} \approx 4k_B T R \Delta f\ . \qquad (2)$$

All of the parameters in Eq. (2) are either fundamental or directly measured. Because Johnson noise is a fundamental representation of temperature (rather than a response to temperature such as electrical resistance or thermoelectric potential), it is immune from chemical and mechanical changes in the material properties of the sensor.

JNT has been applied to in-core temperature measurement for more than 30 years [1], and more generally, Johnson noise has been used for temperature measurement for more than 50 years [2]. Oak Ridge National Laboratory (ORNL), the Korean Atomic Energy Research Institute (KAERI), and the Ohio State University (OSU) have recently completed an International Nuclear Energy Research Initiative (I-NERI) project on implementing JNT for hot-leg temperature measurement.

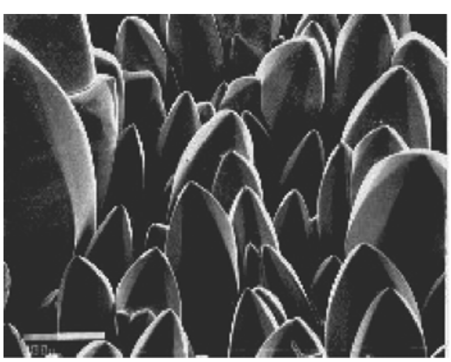
3. Nuclear Power Implementation

3.1 RT Overview and Challenges

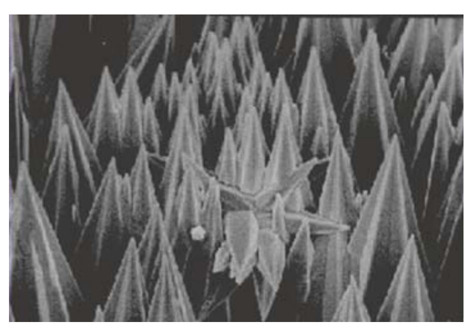
Radiation-based temperature measurement can be made using brightness within a narrow wavelength band. Such a device is referred to as a single-color pyrometer. These devices measure the intensity of intercepted thermal radiation. Band selection is determined by the temperature range and the type of material to be measured. Single-color pyrometers provide grossly errant (non fundamental) measurements of temperature for situations involving varying emittance of the radiating object or any other factor that attenuates or distorts the photon path. An improvement on the single-color pyrometer is the ratiometic or two-color pyrometer, which measures temperatures based on two (or more) discrete wavelengths. The ratio of the brightness in separate wavelengths reduces uncertainty introduced by variation in the absolute intensity. Thus, the advantage of ratio measurement is that temperature readings are more independent of emissivity fluctuations and sight path obscuration. By increasing the number of colors measured, the method becomes a point wise reconstruction of Planck's blackbody curve. The more points used, the less detrimental the effects of emittance uncertainty and spectrally dependent optical path attenuation. With a many-point spectral measurement, the thermometry system is answering the question: "At what temperature must the object be such that it would generate a blackbody curve of the measured shape?"

To realize a fundamental, material-independent temperature measurement, however, the condition of the surface needs to be removed from the photon emission probability. This can be implemented by placing a blackbody emitter in good thermal contact with the surface whose temperature is being measured. The central problem with implementing a thermally contacting blackbody in a GenIV reactor environment is material compatibility of the blackbody with both the reactor component materials and the surrounding air. All of the GenIV concepts call for high core exit temperatures. This limits the choice of structural materials to carbon-based materials, refractory alloys, or high-nickel-content alloys (at lower temperatures).

Although carbon is a preferred high-temperature, blackbody material because of its high emissivity, carbon will react with many high-temperature structural materials and oxidizing environments such as a noninert gas-filled containment. A blackbody fabrication technique, which is more generally compatible, is to employ a highly pocketed surface of the same material as the component surface in which light will experience multiple reflections in the emission process. "Black" tungsten or rhenium surfaces are commonly implemented in this form. These highly dendritic surface morphologies are produced by chemical vapor deposition (CVD), which provides emissivities greater than 0.95 and continuous operating capability to 3300 K. Examples of such surfaces are shown in Figure 1 (a and b). Further, by fabricating the blackbody out of the same material as the outer coating of the reactor component, material compatibility with the local environment is ensured.



(a)



(b)

Figure 1. Tungsten (a) and rhenium (b) grown with dendritic surface morphology to provide a quasi-blackbody emittance. *Source*: Electron microscopy by ULTRAMET ,12173 Montague Street, Pacoima, California 91331

Light emission from the monitored reactor components needs to be transmitted to the measurement electronics located away from the harsh reactor environment. Several different implementations are available to accomplish this, each with their own advantages and weaknesses.

For extreme dose situations, the light must initially be guided from the measurement location using a hollow-core light guide. All known materials darken unacceptably in the intense radiation field of a nuclear reactor core. However, reflective technologies are available that have been shown to withstand comparable environments [3,4]. Conceptually, a hollow-core light guide is simply a mirror that has been formed into a tube (see Figure 2). These guides would be fitted at the distal end with a blackbody device and thermally connected to the reactor component being measured. For lower total dose locations, several different optical transmission technologies are possible: (1) hollow-core light guides with relaxed temperature and radiation tolerance (meaning less exotic construction materials); (2) optical fibers; and (3) relay optics (i.e., telescope). Hollow-core light guides for temperatures below 800 K can be constructed of materials more easily processed than refractory metal alloys [5,6]. For total doses up to about 10^4 Gy, pure silica core, fluorosilica clad, multimode optical fibers are suitable light guides [7]. Relay optics are another alternative for transmitting the light back to the measurement electronics. This implementation, however, does not provide an enclosed light path and is therefore subject to fouling, making the implementation nonfundamental in all but very clean environments.

Figure 2. Hollow-core light guide concept

A highly stable, relatively radiation-tolerant, spectrally sensitive light measurement system is required to measure the emerging light. The spectral selection is typically implemented using an optical grating and a spatially addressable photodetector. Traditionally, optical measurements in high-radiation environments have been made using vacuum-tube-based cameras because of their very high radiation tolerance. The main limitations of photoconductor-based cameras are their price, their relatively larger mass, and their physical fragility. Solid-state photodetectors are currently almost universally employed for non-high-radiation environments. Current-generation, radiation-hardened, charge injection device (CID) type solid-state cameras continue to function in radiation environments (to 10-kGy total dose) with small radiation-induced drift. While highly stable, neither of these optical measurement techniques are fundamental and, therefore, depend more fully on careful engineering to achieve low, long-term measurement uncertainty.

3.2 JNT Overview and Challenges

JNT is best understood as a continuous, first-principles recalibration methodology for a conventional resistance-based temperature measurement technique. The traditional method of directly measuring temperature from a resistance temperature detector (RTD) has unavoidable, unacceptable drift. JNT measurement is applied in parallel to the RTD lead wires of the resistance measurement circuit without altering the traditional resistance measurement circuit.

One significant advantage of JNT is that the actual resistive element is not required to follow a particular temperature to resistance curve. This allows consideration of high stability, high mechanical strength alloys or even a cermet as the temperature transducer—likely significantly increasing the lifetime and reliability of the sensor element. While the JNT amplifier electronics restrict the allowable range of transducer resistance shift with temperature to roughly a factor of three around operational resistance of tens or hundreds of ohms, the exact shape of the resistance to temperature correspondence is not otherwise constrained. Conventional industrial RTD elements are composed of high-purity, well-annealed platinum to achieve a repeatable resistance to temperature correlation. However, RTDs are not industrially deployed at temperatures over 850°C and are often restricted to temperatures less than 450°C for high-accuracy deployments. As the deployment temperature increases, the coefficient of thermal expansion (CTE) mismatch between the platinum element and the support structures exerts progressively greater and greater amounts of stress onto the temperature measurement element shifting its calibration. This is compounded by the softening of platinum at temperatures over ~650°C and the overall increase in impurity atom mobility at higher temperatures.

To make a temperature measurement using Johnson noise, the frequency response of the measurement system must be known as well as the sensor resistance. Temperature is then computed by dividing the power spectral density of the noise voltage by $4k_BR$. Because of the statistical nature of the voltage measurement, there is uncertainty in the solution, which is progressively decreased by increasing the integration time of the measurement.

A direct measurement of the Johnson noise for temperature determination presents several challenges. First, the amplifier gain needs to be both known and stable. Second, the amplifier passband and filtering effects of connection cabling must be known to within the required measurement accuracy. Finally, the resistance of the sensor must be independently and accurately measured. To avoid these difficulties, early Johnson noise thermometers performed a ratio of two noise voltage measurements, one with a resistor at the measurement temperature and the other at a known temperature, switched onto a single amplifier channel. However, changing the connection of the sensor to the high-gain measurement circuit introduced noise and decreased reliability.

More modern JNT architectures implement the resistance and noise voltage measurement in parallel. A block diagram illustrating the combined measurement process is shown in Figure 3. In the diagram, the RTD, which is exposed to process temperature, exhibits both a resistance value and Johnson noise. These two signals are separable and thus can be processed independently. The RTD's resistance temperature value is compared with the Johnson noise temperature and a correction is made to the transfer function. This correction can be made quasi-continuously or on a periodic basis depending on the RTD's drift and target uncertainty values. As shown in Figure 3, the output of the RTD resistance measurement system with Johnson noise correction periodically applied provides a prompt temperature measurement with consistently high accuracy.

The Johnson noise augmentation to RTD temperature measurement requires additional electronics. The electronics require Junction Field Effect Transistor (JFET)-based high-gain amplifiers and digital signal processing logic. JFETs are a majority carrier type of transistor that do not require oxide insulation layers. Consequently, when properly implemented, JFETs are much more radiation-tolerant than alternate topologies. Johnson noise is fundamentally a small signal, whose frequency content is significant to the measurement. The capacitance of long cables reduces the amplitude of high-frequency signals; therefore, the Johnson noise measurement is restricted to low frequencies for long cable lengths. Lower bandwidth increases the interval between Johnson noise corrections of the RTD transfer function.

The most significant practical difficulty in implementing JNT is eliminating the contaminating noise sources arising from other phenomena. The noise contribution from the amplifier circuitry can be greatly decreased by connecting the RTD in parallel to two separate high-input impedance amplifiers. The output of these amplifiers is partially correlated since each consists of the sum of a correlated noise voltage and uncorrelated amplifier noise voltage. If two Johnson noise amplifier signals, connected to the same resistance, are combined and time averaged, the correlated part of the noise will persist, but the uncorrelated amplifier noise will approach zero. Figure 4 illustrates the concept of cross-correlation; the measured voltage from one amplifier channel is Fourier transformed and multiplied by the other to form a cross power spectral density (CPSD), effectively eliminating the noise contribution from the amplifier electronics.

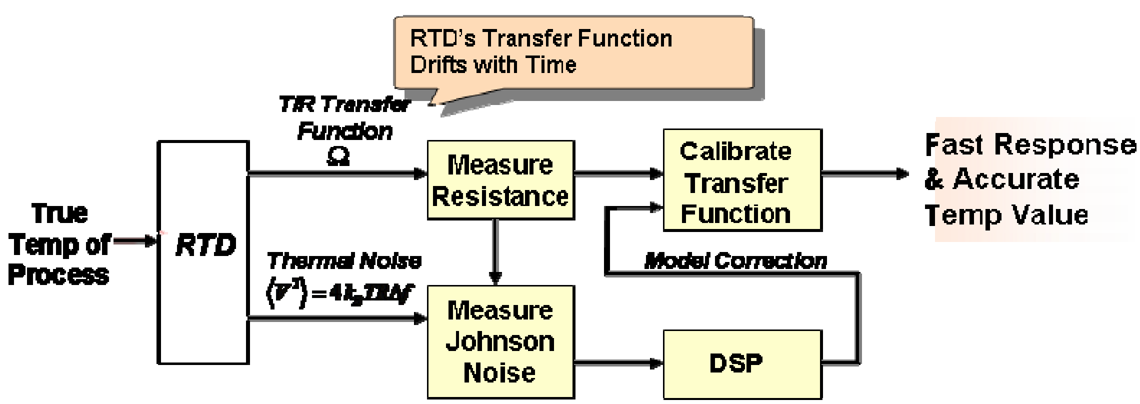


Figure 3. JNT measurement process block diagram

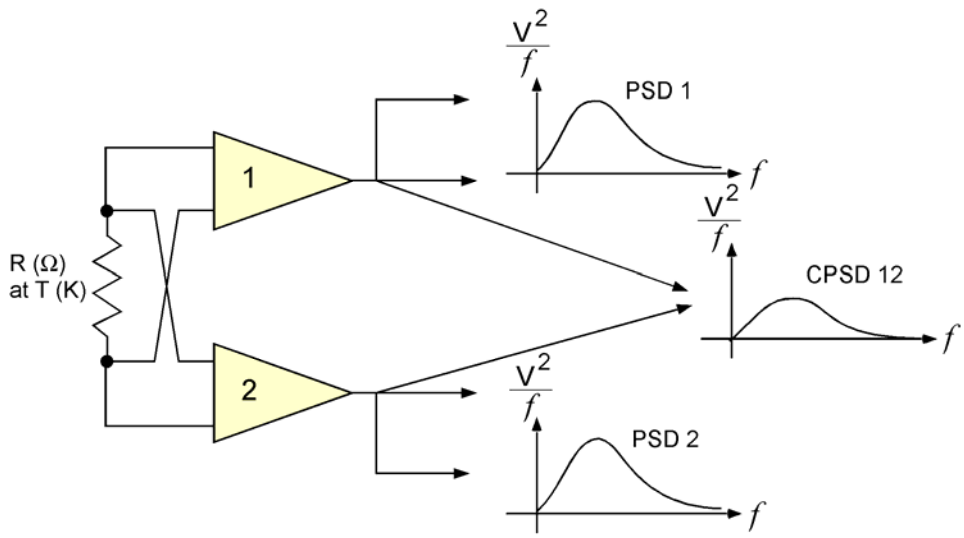


Figure 4. Power spectral density of each amplifier channel containing both correlated and uncorrelated noise and the CPSD function from both amplifiers containing only correlated noise.

Johnson noise is a small-signal phenomenon. For a 300-K measurement using a 100-Ω resistor and a 100-kHz frequency band, the root of the mean squared noise voltage is approximately 4×10^{-7} V. As such, electromagnetic interference spikes and microphonics are two of the biggest problems for a practical implementation of JNT. In many situations, these effects can completely dominate the noise measurement. This puts a premium on well-implemented grounding, shielding, and filtering. A complementary technique to reduce these effects is to use both knowledge of the spectral energy content of Johnson noise and digital signal processing to recognize and eliminate interferences. Typically, narrowband electromagnetic interference (EMI) appears as spikes in the long-term average CPSD that can be recognized and removed with only a small reduction in measurement bandwidth as illustrated in Figure 5.

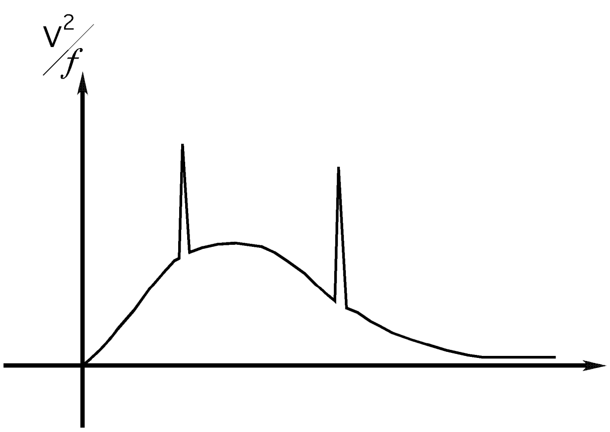


Figure 5. CPSD with narrowband EMI spikes

Typical cables exhibit a capacitance of approximately 100 pF/m. The maximum available bandwidth vs cable length for a 100-Ω RTD that exhibits loss of less than 0.1% of the noise power is shown on Figure 6, given a 50-pF input capacitance of the field-effect transistors (FET). If support electronics were located 25 m from the sensor, the JNT would have a maximum available bandwidth of approximately 20 kHz, given the assumptions above. Under the high-temperature and radiation environment of a GenIV nuclear reactor, the cable capacitance will change over time. One way of compensating for the cable effect is to periodically measure its input impedance and calculate its transfer function. However, the best technique remains to locate the first-stage amplifier near the sensor.

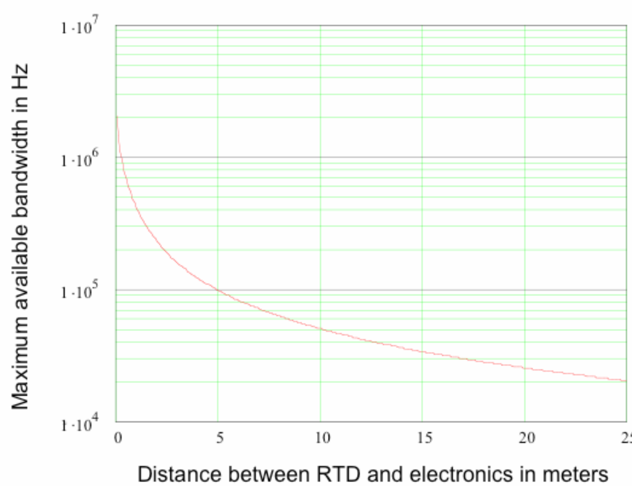


Figure 6. Cable bandwidth as a function of length.

4. Conclusions

A principal difference between GenIII+ and GenIV reactors is the progressively higher temperatures. This directly increases the rate of drift of the thermometry probes. Accurate temperature measurement is required to minimize the margin the plant is required to maintain to account for measurement uncertainty as well as to decrease unnecessary component stress. The physical properties of all known materials degrade significantly over time when subjected to a harsh (high radiation and high temperature) GenIV reactor environment. Some form of an *ab initio* type thermometer is therefore highly advantageous. A comparison of the strengths and weaknesses of the two techniques is shown as Table 1.

Table 1. Comparison of strengths and weaknesses of RT and JNT

	RT	JNT
Most significant limitation for reactor *Ab Initio* implementation	Light-guide reflectance efficiency changes with time, dose, and temperature	Spectrally-dependent cable shifts result in signal distortion with time, dose, and temperature
Largest technology uncertainty	High-temperature, high dose light-guide performance	Radiation-tolerant, high-gain amplifier electronics availability and stability
Most advantageous implementation conditions	Long separations between reactor and measurement electronics with only short light-paths in high-dose environments	High transducer doses with reactor temperatures <1700 K, and electronics located in a well-shielded environment near the reactor

Both RT and JNT can be implemented in fundamental forms such that drifts in the properties of the transducers do not alter the measured temperatures. However, both of the methodologies require sophisticated implementations to achieve drift-free performance that have not been demonstrated under environmental conditions that are representative of a GenIV reactor. Consequently, significant amounts of temperature measurement engineering remains before long-term reliable temperature measurement systems for GenIV can be developed.

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