ORNL/LTR-2015/358

Letter Report of the Self-Calibration Testing of the Johnson Noise Thermometry System

C. L. Britton
M. J. Roberts
N. D. Ezell
D. Holcomb

August 2015

Approved for public release; distribution is unlimited.

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

CONTENTS

Page

LIST OF FIGURES

Figure **Page**

ABSTRACT

Temperature is a key process variable at any nuclear power plant (NPP). The harsh reactor environment causes all sensor properties to drift over time. At the higher temperatures of advanced NPPs, the drift will be both larger and more rapid. The allowable reactor operating temperature must be reduced by the amount of the potential measurement error to provide an adequate safety margin. Decreasing the temperature reduces the plant's thermal efficiency. Johnson noise is a fundamental expression of temperature and, as such, is immune to drift in a sensor's physical condition. Small modular reactors (SMRs) place a higher value on long-term stability in their temperature measurements because they produce less power per reactor; therefore, they cannot afford as much instrument recalibration labor as larger reactors receive. The purpose of the current project—conducted under the Instrumentation, Control, and Human-Machine Interface (ICHMI) technology area of the US Department of Energy Advanced Reactor Technologies (ART) research and development program—is to develop and demonstrate a drift-free Johnson noise-based thermometer suitable for deployment near cores in advanced reactor plants.

This report summarizes the self-calibration testing of the Johnson Noise Thermometry System developed at Oak Ridge National Laboratory. The purpose of the testing is to demonstrate that the Johnson noise thermometry (JNT) technique will accurately measure temperature of a resistive element independent of any changes in the resistor value. In other words, even if the resistance to temperature relationship of the resistance temperature detector in the JNT system changes, the JNT system will continue to report the correct temperature.

1. BACKGROUND

Reactor core outlet temperature measurement is used as an indication of the thermal performance of each fuel assembly and to maintain an adequate thermal margin to fuel damage. Johnson noise thermometry (JNT) was demonstrated for in-core temperature measurement 40 years ago [1], and more generally, Johnson noise was demonstrated for temperature measurement more than 60 years ago [2]. An overview of the application of Johnson noise to high-temperature reactors was published in 2005 [3]. However, despite the decades of admittedly intermittent effort, no Johnson noise thermometry instrument intended for use near cores has reached the commercial market. The underlying reason for this is that Johnson noise is a small-signal phenomenon. Measuring the Johnson noise of a resistive element in isolation from all of the additional electrical signals that inevitably occur in a plant environment is technically daunting. This project relies on a combination of the characteristic shape of the Johnson noise power spectrum, recent advances in digital signal processing, and progressive improvements in the measurement electronics design to isolate and extract the Johnson noise signal.

Johnson noise is a first-principles representation of temperature. Fundamentally, temperature is merely a convenient representation of the mean translational kinetic energy of an atomic ensemble. Since Johnson noise is a fundamental representation of temperature rather than a response to temperature, such as electrical resistance or thermoelectric potential, Johnson noise is immune from chemical and mechanical changes in the material properties of the sensor. One consequent advantage of JNT is that the actual resistive element is not required to follow a particular temperature versus resistance curve. This allows consideration of high stability, high mechanical strength alloys, or even a cermet element 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 an operational resistance of tens or hundreds of ohms, the exact shape of the resistance-to-temperature correspondence is not otherwise constrained.

The present implementation of JNT is best understood as a continuous, first-principles recalibration methodology for a conventional resistance-based temperature measurement technique. The traditional method of inferring the sensor temperature from measuring its resistance and employing a fixed response curve has unavoidable, and potentially unacceptable, drift. Johnson noise measurement is applied in parallel to the resistance temperature detector (RTD) lead wires of the resistance measurement circuit without altering the traditional resistance measurement configuration. Because a traditional four-wire resistance temperature measurement remains within the planned JNT implementation, the JNT system has the potential to minimize the licensing issues associated with deploying advanced, software-based signal processing in safety-related measurements at nuclear power plants (NPPs). The Johnson noise measurement does not alter the prompt response of the thermometer, but instead provides a gradual correction to the RTD's resistance versus temperature relationship.

JNT has the potential to become a key temperature measurement technology throughout NPPs, including in and near cores where the large, high-energy neutron flux makes all commercially available, low-uncertainty thermometry techniques unusable. The principal expense in a Johnson noise measurement system is the cost of developing the technology to extract the small JNT signal from competing noise sources. Neither the electronics to implement JNT nor the well-shielded transducer and cabling are especially expensive. As such, well-implemented JNT has the potential to compete economically with other low-uncertainty thermometry techniques at high temperatures throughout NPPs. Further, JNT has the potential to become the preferred thermometry technique throughout the process control industry because of its robustness and low measurement uncertainty at a reasonable price.

2. SIGNAL PROCESSING REQUIREMENTS

The Nyquist equation describes the voltage produced by the motion of the electrons within a resistor at a given temperature. For frequencies below a few gigahertz, Eq. (1) shows the relationship among the absolute temperature of a resistor (T), its resistance (R), the frequency band of measurement (Δf), and the measured mean-square noise voltage.

$$\overline{V^2} = 4k_B TR\Delta f \qquad (1)$$

where k_B represents Boltzmann's constant (1.38×10^{-23} joules/Kelvin).

A direct measurement of the Johnson noise for temperature measurement has 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 well known to within the required measurement accuracy. Finally, the resistance of the sensor must be measured independently and accurately. 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 [3].

Another implementation restriction for Johnson noise thermometry in reactors is the capacitive effect of the cable connecting the sensing resistor to the first stage amplifiers. If the cable has significant capacitance, it will block the high frequency portion of the sensor noise before it reaches the measurement system. This filtering of the upper frequencies reduces the bandwidth of the Johnson noise signal. Under the temperature and radiation environment inside the containment structure of an NPP, the cable capacitance will exhibit some change over time. We are presently designing the measurement electronics to be positioned outside of the containment environment, which places a minimum input cable length of approximately 25 m between the RTD and the first stage amplifier electronics. This configuration adds a great deal of capacitance (many nanofarads) and complicates the front-end electronics design. We are currently correcting for this effect using the pilot-tone sweeping technique that measures channel gain and frequency variations.

Two additional signal-processing techniques were investigated previously to minimize exogenous noise [4]. In the first technique, the temperature measurement resistor is connected in parallel to two separate high-input impedance amplifiers. The output of these amplifiers is partially correlated because 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 1 illustrates the concept of cross-correlation; the measured voltage from one amplifier channel is Fourier transformed and correlated with the measured voltage from the other to form a cross power spectral density (CPSD) measurement, effectively eliminating the noise contribution from the amplifier electronics.

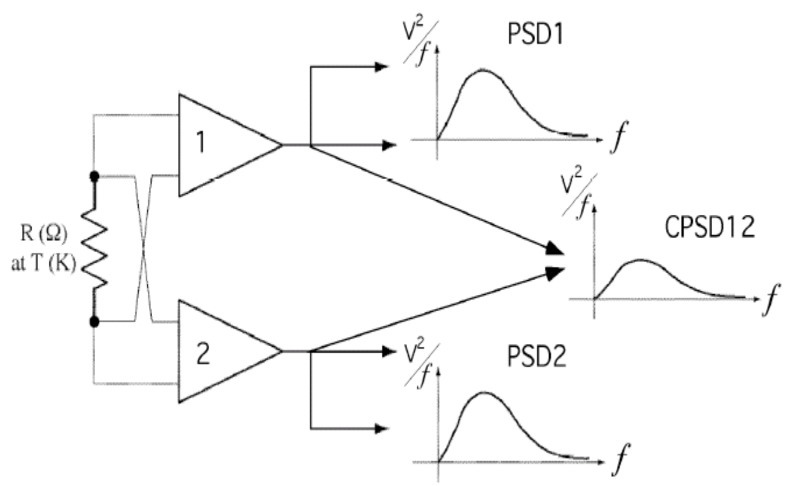


Fig. 1. Power spectral density function (PSD) of each amplifier channel containing both correlated and uncorrelated noise and the cross power spectral density (CPSD) function from both amplifiers containing only correlated noise.

Johnson noise has a flat (white) spectral energy distribution. The shape of the power-spectral density functions displayed in Figs. 1 and 2 is a result of the combined effects of filtering out both low and high frequencies from the noise and the frequency-dependent gain of the amplifier circuit. Low-frequency filtering is applied to eliminate non-thermal noise generated by mechanical vibrations. These microphonic signals are limited to less than a few tens of kilohertz. The upper-frequency filtering is applied both to avoid aliasing higher frequencies into the measurement band and to minimize the impact of sensor-to-amplifier cable capacitance-induced restriction of high frequency signal transmission. The CPSD function has units of volts squared per hertz and expresses the power content per unit frequency of the measured noise signal. It is derived from the individual channel PSDs as shown in Fig. 1.

Microphonics and electromagnetic interference (EMI) spikes are two of the largest contributors of exogenous noise in JNT field implementation. In many situations, these effects can dominate the Johnson noise measurement completely. The existence of large, competing signals puts a premium on well-implemented grounding, shielding, and filtering. The second noise rejection technique uses both knowledge of the spectral energy content of Johnson noise and digital signal processing to recognize and eliminate narrowband electromagnetic interferences. Narrowband EMI always 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 Fig. 2.

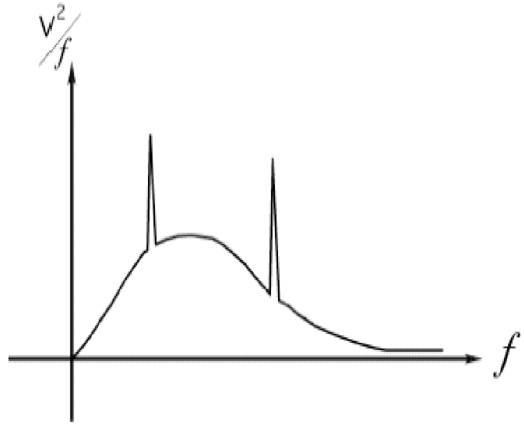


Fig. 2. Cross power spectral density with narrowband electromagnetic interference spikes.

3. PRESENT JNT IMPLEMENTATION

The current US Department of Energy project is focused on implementing a dual-mode resistance and Johnson noise thermometer in a rugged, integrated prototype form. The resistance measurement serves the dual purpose of providing the necessary impedance measurement for the Nyquist equation as well as providing a prompt temperature measurement. Because Johnson noise is a stochastic process, a statistically significant amount of time is required to perform a measurement. The temperature measurement in the dual-mode thermometer, therefore, is made as a simple resistance measurement whose resistance-to-temperature conversion is quasi-continuously updated using Johnson noise. Figure 3 shows a schematic illustrating the measurement process. CPSD provides the resistor noise voltage. The sensor resistance is measured independently, so the remaining variables that have to be known to obtain temperature from the voltage measurements are the amplifier gain as a function of frequency and the effective measurement frequency band (Δf). The technique currently used to obtain the gains is to calibrate the measurement initially using a known temperature and treating the amplifier gain and the effective measurement frequency band thereafter as a single constant.

High-gain, wide-band Johnson noise preamplifiers with a precision four-wire ohmmeter have been implemented in high-density discrete-component electronics. A continuous amplifier gain calibration scheme also has been implemented. The digital signal processing logic has been implemented in LabVIEW™ on a desktop computer using a commercially available high-speed 14-bit analog–digital converter (ADC)/data acquisition module. The preamplifier head and resistance probe have been packaged in a shielded aluminum enclosure, and a coaxial signal interconnection scheme has been implemented. The preamplifier section contains two identical differential-input junction field-effect transistor (JFET) preamplifiers/filters/gain blocks, each with a voltage gain of approximately 80 dB and a center frequency of approximately 20 kHz. The calibration system is implemented using a swept-frequency (FM) oscillator that supplies the calibration signal over the noise bandwidth of the amplification chain by sweeping continuously between 1 and 100 kHz; it is coupled directly into the front-end preamplifier. A submilliamp current also is supplied to the input, and a separate differential amplifier (ohmmeter circuit) measures the voltage drop across the RTD. The ADCs and voltage-sweep system are remotely programmable from the LabVIEW™ software.

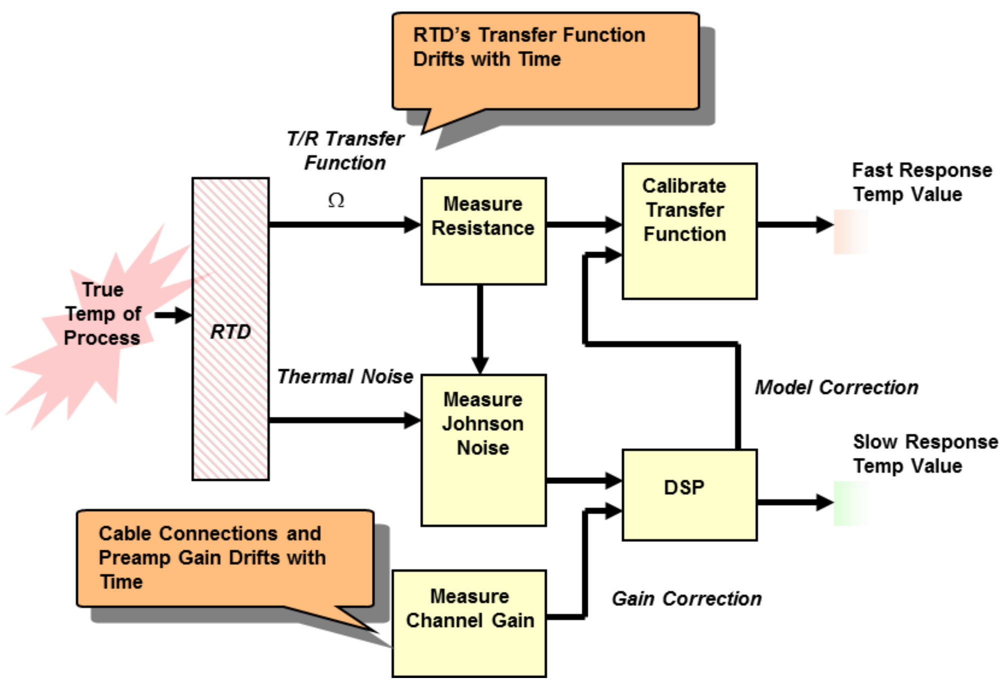


Fig. 3. Johnson noise thermometry measurement process schematic (*Notes:* DSP = Digital Signal Processor; T/R = Temperature/Resistance).

The signals processed by the data-acquisition system consist of two Johnson-noise measurement channels and one DC resistance measurement channel. The Johnson-noise channels consist of amplification followed by multiple poles of low-pass filtering. The DC resistance channel has a front-end differential receiver amplifier similar to those of the Johnson-noise channels. The signal then passes through several multi-pole high pass filters. The signals out of these three channels are then sent to a computer-based digital-signal processor (DSP) using a four channel, 2 M sample per second ADC board.

4. RTD RESPONSE TO TEMPERATURE

Platinum resistance temperature detectors are ubiquitous in industry. They are well-understood, mature devices that are relatively easy to use. A common representation of resistance of an RTD at a given temperature *t* is calculated by the Callendar–Van Dusen (CVD) equation [5] which is

$$R(t) = R(0)[1 + A \times t + B \times t^2 + (t - 100) \times C \times t^3] \quad (2)$$

where A, B, and C are constants derived from resistance measurements at various temperatures, and *R(0)* is the resistance measured at 0°C. The RTD exhibits a nonlinear parabolic resistance as a function of temperature. As long as this relationship stays constant, the RTD can be used for accurate temperature measurements. In actual use, there are changes in material properties that occur with aging or temperature effects—or both— that can change this relationship. It is for this reason we are pursuing JNT as an adjunct to the above relationship.

5. HOW THE RESPONSE IS USED IN THE CURRENT SYSTEM

The system implements the CVD equation in LabView but solves for temperature given the constants and *R(0)* and *R(t)*. The ohmmeter part of the system is calibrated in two steps. First, three or four different temperatures are measured with the desired RTD connected to the JNT system. At each temperature, the JNT voltmeter output is read, and the RTD is then connected to a four-wire commercial ohmmeter, which then records the RTD value. After the desired number of points, a linear fit of the voltmeter response of ohms vs. voltage is performed and entered into the JNT software. *R(0)* is then measured by submersing the RTD in an ice bath and measuring the resistance using the JNT system. This value is entered into the software, thus completing the DC resistance calibration. The resistance calibration should be accurate for any RTD connected to the JNT system, but the value for *R(0)* will need to be determined for each RTD.

6. TESTING TECHNIQUES

The goal of testing was to illustrate the self-calibration capability of JNT. This comes about from the fundamental nature of the measurement. If the resistance vs. temperature calibration of an RTD changes because of aging, the temperature value of the RTD still should be available from the Johnson noise signal because the DC resistance and noise are measured continuously (Eq. [1]).

The change in calibration of an RTD comes about because of the change in material properties of the platinum over time and temperature. Because the change is very slow and relatively continuous, we have not been able to simulate the change within a reasonable amount of time. The team considered using actual RTDs for the test but could not generate any techniques that would allow us to deterministically change the resistance of an RTD by a small amount (<5%). The following techniques were considered:

1. *Use of a fixed resistor with relays to insert different values in series*. This would accomplish the desired resistance change but would add an enormous amount of switching noise every time the resistances were changed unless the program was stopped.
2. *Use of a fixed resistor with relays to insert different values in parallel*. This would exhibit the same effect as that exhibited in the first technique.
3. *Use of a fixed resistor with some configuration of a potentiometer*. The problem would be the same as before. When the wiper was changed, there would be noise unless the program was stopped.
4. *Use of a fixed resistor with a large value soldered across it and cutting the large value off during a run*. Noise will be added unless the action is accomplished between acquisition blocks (time between cycles is a few seconds).

The resistance clipping technique was selected as the simplest to implement. Implementing a pause function in the data acquisition software was key to being able to discretely change the sensor resistance to simulate prompt damage. The pause allows an entire cycle to finish after the on-screen pause switch is activated and the existing data retained. After restarting, the measurement continues taking data with the system in the new state. Technique number 4 still appears to be the best option because the resistors are intimately connected and therefore should remain at the same temperature. In addition, we were able to easily shield the resistors from EMI and keep them at a constant room temperature. Our procedure consisted of measuring with a fixed resistor or parallel combination of two resistors, and then

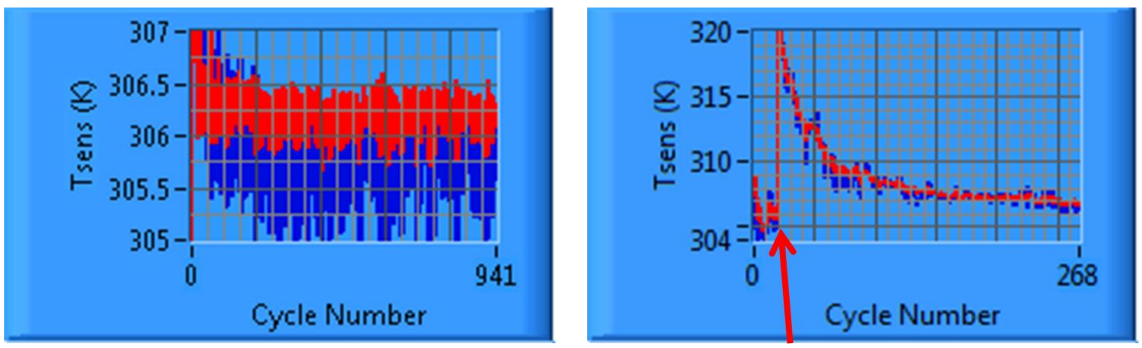
- pausing the run and soldering on another parallel resistor,
- pausing the run and clipping off a parallel resistor soldered to the main 100-ohm resistor, or
- waiting until the brief window at the end of a cycle and clipping off a parallel resistor from the main 100-ohm resistor.

A small wire cutter was used to clip resistors, which were standard 1% metal film, 1/8 W, axial-leaded devices. The main 100-ohm resistor was soldered directly onto a multi-pin connector used on the new JNT system. The measurement maintained the four-wire measurement configuration up to the resistor side of the connector.

7. RESULTS OF THE TESTS

As previously described, we performed tests using fixed resistors either alone or in parallel. The particular test shown in Fig. 4 is where a 100-ohm resistor was soldered in parallel with a 1.96 KΩ resistor for the low value, and the 100-ohm resistor was tested alone for the high value. The actual values resulted in 100.159 ohms and 95.49 ohms, respectively. At cycle 20, the run was paused, and one end of the 1.96 KΩ resistor was clipped off the 100-ohm resistor, leaving only the 100-ohm resistor connected. As can be seen in the right-hand plot, the next cycle of the run uses the previously acquired variables to calculate the temperature, which appears to have increased greatly. The difference, however, is only because the resistance has jumped 5%. Given the limited statistics this run started with (20 cycles), approximately 250 cycles are required to settle back to the original temperature.

Another longer run is presented in Fig. 5. This run illustrates the change in resistance after a much longer run. The system was run with a combined resistance (100 ohms in parallel with 39.6 K ohms) of 99.89 ohms for 5 days at constant temperature. The 39.6 KΩ resistor was then clipped off, which resulted in a resistance of 100.148 ohms, a change of 0.26%. The JNT temperature before clipping was 306.188 K; it rose sharply to approximately 307 K when clipped. After the settling time of almost 26 h, the temperature returned to 306.052 K. Based on these measurements, the self-correction time depends on the amount of prior data history before the prompt damage. Note that the actual RTD damage is anticipated to be progressive, not prompt.



Overnight run with 95.49 Ohms
Terminal temperature = 306.225K

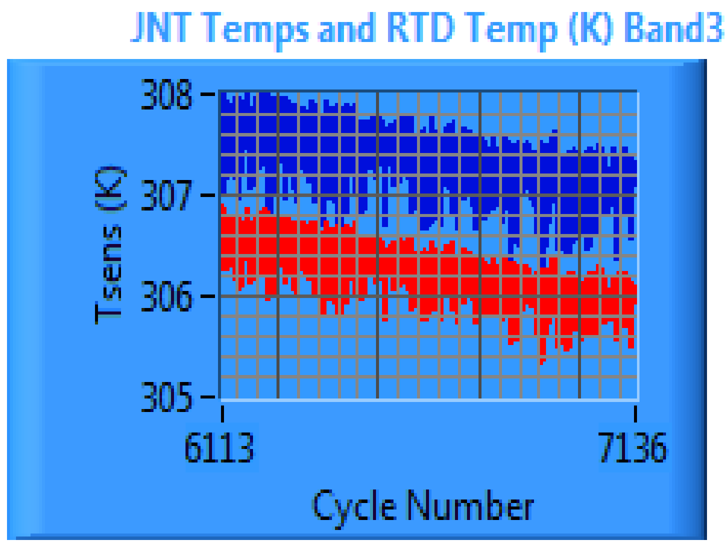
268-cycle run with 95.49 Ohms beginning but changed to 100.159 ohms after 20 cycles.
Terminal temperature = 306.754K

Fig. 4. Test illustrating the temperature measurement of changing resistances.

From observations, it is clear that the more data that is averaged before the changes, the longer the system will take to return to the new value for a step function change. Thus, a final system would include only a limited time window of prior data. As time passes, earlier noise data becomes less and less important, which would indicate that some sort of sliding average of readings might be the best approach to measurement. This would allow the user a tradeoff between reducing uncertainty (long average times) and improved transient response (short average times).

8. NOTIONAL IMPLEMENTATION IN AN ALGORITHM

Platinum resistance temperature detectors for use in nuclear reactors normally are calibrated over a temperature range from 0°C to 661°C (the melting point of aluminum). In 1968 (and again in 1990), the CVD equation was replaced by higher-order polynomial relationships. Currently two equations are used by standards labs—a 12th order polynomial between 13.8033 K and 273.16 K and a ninth order polynomial from 0°C to 961.78°C. The actual calibration of a real (as opposed to an idealized) RTD in the range of interest in reactor temperature measurements is done by making resistance measurements at multiple temperatures covering a range of temperatures expected during reactor operations and fitting a polynomial to those resistance–



7136-cycle run with 99.89 Ohms
beginning but changed to 100.148 ohms
after 5800 cycles.

Fig. 5. Long test illustrating the settling time of changing resistances.

temperature (RT) pairs. A polynomial degree of three is usually sufficient to fit the data with acceptably small uncertainties for use in reactor control. JNT can be used to update the calibration of a platinum RTD in situ in a reactor during its normal operation, without disturbance. An RTD would start with a standards lab calibration using multiple RT pairs at the beginning of the reactor's life. At regular time intervals, new RT pairs then would be determined through JNT. These would be added to the original RT pairs, and a new calibration curve would be fit to all the RT pairs to form a revised calibration. Over time, the weighting of older RT pairs in the polynomial fitting process would be decreased gradually to keep the calibration current and accurate.

Normal reactor operation would proceed at fairly constant temperature. Therefore, the new RT pairs would be clustered around that operating temperature. If the reactor is shut down periodically for maintenance or for other reasons, JNT could be used to acquire RT pairs at lower temperatures. The most important need for accurate temperature measurement is in a relatively small range around the nominal operating temperature, and that is where most of the JNT data would lie.

9. ACKNOWLEDGEMENTS

The authors appreciate figures and text provided by Roger Kisner and Lou Qualls of Oak Ridge National Laboratory.

10. REFERENCES

1. H. G. Brixy, “Temperature Measurement in Nuclear Reactors by Noise Thermometry,” *Nuclear Instruments and Methods* 97, no. 1 (November 1971): 75–80.
2. J. B. Garrison and A. W. Lawson, “An Absolute Noise Thermometer for High Temperatures and High Pressures,” *Review of Scientific Instruments* 20, (1949): 785–94.
3. D. E. Holcomb, R. A. Kisner, and C. L. Britton, Jr., “Fundamental Thermometry for Long-Term and High-Temperature Deployment in Generation IV Reactors,” in *Proceedings of the International Symposium on Future Instrumentation and Controls 2005* Tonyeong, Republic of Korea, November 1–3, 2005.
4. R. Kisner, et al., “Johnson Noise Thermometry for Harsh Environments,” in *Proceedings of the 2004 IEEE Aerospace Conference*, Big Sky, MT, March 6–14, 2004.
5. M. S. Van Dusen, “Platinum Resistance Thermometry at Low Temperatures”, Journal of the American Chemical Society, Vol. 47, pp. 326-332.