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IN SITU CALIBRATION OF NUCLEAR PLANT RESISTANCE THERMOMETERS USING JOHNSON NOISE*

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Johnson noise power measuring techniques have been used to calibrate platinum resistance thermometers (PRTs) installed in an operating nuclear plant, achieving agreement with the dc calibration of better than 0.1% or 0.5°F at the normal operating temperature of 585°F. In this application, PRTs with an ice-point resistance of 200 ohms were connected to a test station with 4-wire cables approximately 100 feet long. Methods were developed for in situ cable characterization and quantitative measurement of and correction for non-thermal induced noise.

Problem Statement:

Operating light water reactor nuclear plants require an accuracy of 0.2 to 0.65% in the temperature measurements made by wide-range PRTs installed at the inlets and outlets of the vessel or the steam generator. After several years' operation, these PRTs may drift by as much as 1%. Removal and recalibration of the PRTs in the laboratory is undesirable, since their reinstallation may adversely affect their response time or lead to wiring errors. An in situ method for calibration of PRTs that does not assume isothermal conditions, does provide an absolute temperature standard, and does not require any modification of the sensor or its cabling would significantly improve the operation of existing nuclear reactor plants.

Measurement Method:

The Johnson noise power thermometer conceived by Borkowski and Blalock at ORNL can be used to determine independently the absolute temperature and the electrical resistance of any resistor (including a PRT) from measurements of the noise voltage and noise current at the accessible terminals of the device. These measurements are made at microvolt and nanoamp levels in a passband centered at 47 kHz. Major problems in implementing this method under field conditions are (1) determining the effects of long cables connecting the PRT to accessible terminals and (2) distinguishing between thermal (Nyquist) noise and non-thermal (EMI) noise picked-up in the cables and sensor. Methods were developed for (1) determining the cable transfer function from impedance measurements made at the input of the extension cables and for (2) quantitative measurement of the induced EMI, using the Johnson noise measurement apparatus connected between the sensor leads and the cable shield. Additional measurements, using noise, were required to determine the noise contributed by the amplifiers, the effects of long cables and varying resistive loads on the amplifier noise, and the gain of the amplifiers. The gain was determined using a high-level noise source developed at ORNL. A diagram of the circuit involved is shown in Figure 1.

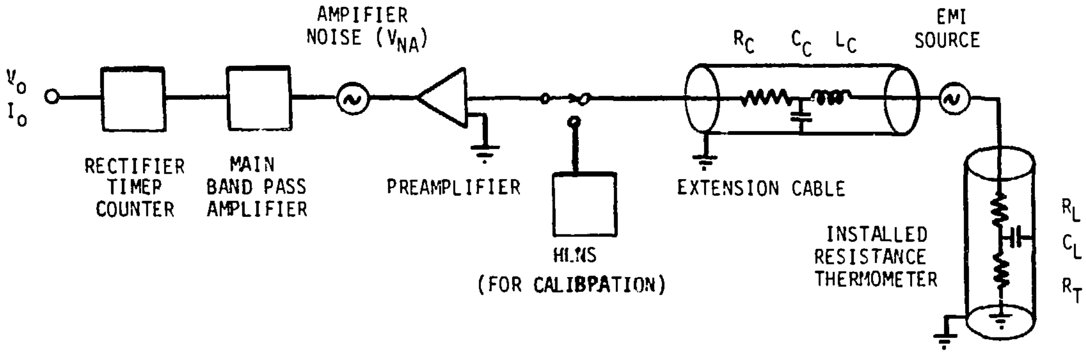
Plant Tests Previously Performed

Field calibrations of resistance thermometers installed in the Diablo Canyon Nuclear plant under hot-functional conditions were conducted in 1979 under EPRI Contract RP 1440-1. These tests made on PRTs with short (20-ft)cables provided agreement between noise temperatures and dc calibrations of better than 0.3%. Noise measurements were made in three different passbands to differentiate between thermal and non-thermal noise, microphonics were detected in one type of PRT, and a difference between dc resistance and noise resistance of about 5% was observed and attributed to skin effect or inductance. Attempts to calibrate PRTs with extension cables longer than about 30 feet were unsuccessful and was felt to be an insurmountable practical constraint.

Noise Transfer Characteristics of Long Cables

The present contract focussed on methods for determining the transfer characteristics of long (greater than 30-ft) extension cables connecting the PRT to a remote junction box by measurements made only at the accessible terminals. Two methods were developed. One, the similitude method, required a measurement of the effective length of the installed cable, using dc resistance, time domain reflectometry, or input capacitance, and relating the characteristics of the installed cable to characteristics of similar cables of various lengths measured in the laboratory. This approach has the virtue of measuring cable properties at the signal levels and in the frequency passband used in the calibration of the PRTs; it has the limitation imposed by the assumption that the installed cable properties are identical to the archive cable characteristics. The second method used input impedance measurements (phase and magnitude) made directly on the installed cable which were related to a 2- or 3-wire model of the transmission line to calculate the transmission function for the cable. Measurements were made at many frequencies covering the passband used in the noise measurements. This method, shown in Figure 2, requires no assumptions about the similarity between installed and archive cable.

Measurements of cable transfer characteristics made in the laboratory and used in the plant showed that, for PRTs with an ice point resistance of 200 ohms (which increased to over 400 ohms at plant operating temperatures) and 4-wire, shielded cables of about 70 pF/ft capacitance, cable transfer functions could be obtained for cables of about 100 ft in length with an accuracy of about 0.1%. For longer cable lengths which could be characterized by this method, the noise signals to the input of the noise-measuring amplifiers would be attenuated so much that at 150 feet, the input signals were comparable to the amplifier noise



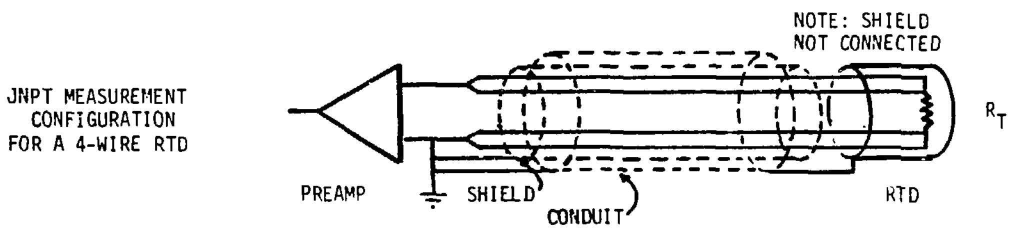
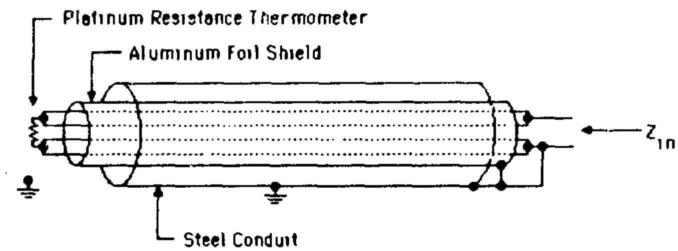


Figure 1. SCHEMATIC FOR JOHNSON NOISE MEASUREMENTS ON INSTALLED RESISTANCE THERMOMETERS

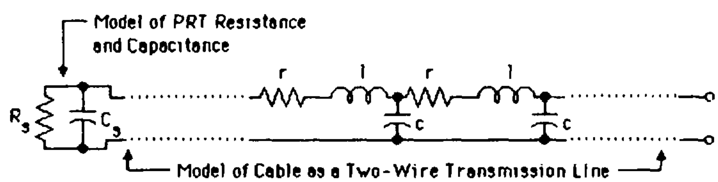
Figure 2

In-Situ Measurement of Cable Properties

From Measurement of Input Impedance (Z_{in}) the Cable Model Parameters (r, l and c) can be determined



From the Model, the Transfer Function of the Cable can be calculated and the Cable Effects can be compensated for



and the calibration uncertainty would exceed several percent. The combined effects of the cable RC roll-off and the amplifier passband are shown in Figure 3.

Measurement Uncertainties

The uncertainty in the Johnson noise calibration of installed PRTs is determined by the stochastic uncertainty in the noise measurements of the sensor signal and the amplifier noise and gain, the characterization of the cable transfer function, and the detection of non-thermal noise in the amplifier output. The stochastic uncertainty is given by the Rice equation: $\Delta S/S = (4BWt_i)^{-1/2}$, where BW is the bandwidth of the amplifiers and t_i is the integration time. For the bandwidth used in these measurements (about 62 kHz) and 100 sec integration time, the limiting stochastic uncertainty is 0.020% for each measurement. Since several measurements are made to determine the noise temperature, the limiting uncertainty in noise temperature for a zero-length cable is 0.028% assuming that the amplifier gain is known, or 0.040% if the amplifier gain is measured each time. For a 100-ft cable terminated by a PRT of 400 ohms at 270C (520F), an uncertainty in cable length of 1% introduces a temperature uncertainty of 0.83% in the similitude method. The cable length uncertainty effect is reduced to 0.12% uncertainty in temperature if the length is reduced to 75 ft and the sensor resistance is halved. Non-thermal EMI was quantitatively determined, at a level of less than 1% of the thermal noise from the PRT, by measuring the noise between the sensor circuit and the cable shield and using the measured values to correct the amplifier output signal.

Plant Tests under the Present Contract

Three field tests of these methods were conducted at the Connecticut Yankee Haddam Neck Nuclear Plant (CYAP): two at shutdown in February 1983 and July 1984, and one at full power in December 1983. CYAP provided an accessible terminal box connected to five PRTs in Loop 4 by extension cables about 100 ft long, archive cables of various lengths, several spare PRTs, dc calibrations for the plant PRTs, and technical support for the field tests. The plant temperatures were held steady to better than 1F during the tests. Three of the PRTs were equipped with padder and trimmer resistors and could not be calibrated by these methods; two were 4-wire PRTs without padders and trimmers as shown in the schematic Figure 4. Lengths of the installed cables were measured by several electrical methods but are uncertain by 0.5 ft as shown in Table 1. Using the similitude method of determining cable transfer function, the resulting best agreement between noise temperatures and dc calibration temperatures was 0.72% uncorrected for EMI and 0.45% (4.7F) corrected for EMI at the operating temperature (585F) and 0.01% at shutdown (113F). The uncertainty in the similitude method is 0.4%. Using direct impedance measurements to characterize the installed cable and then to correct the amplifier input signal for the actual noise generated by the PRT, the agreement between noise and dc

Figure 3

ATTENUATION OF NOISE POWER BY LONG RTD EXTENSION CABLES

AREA UNDER CURVES IS THE MEASUREABLE NOISE POWER

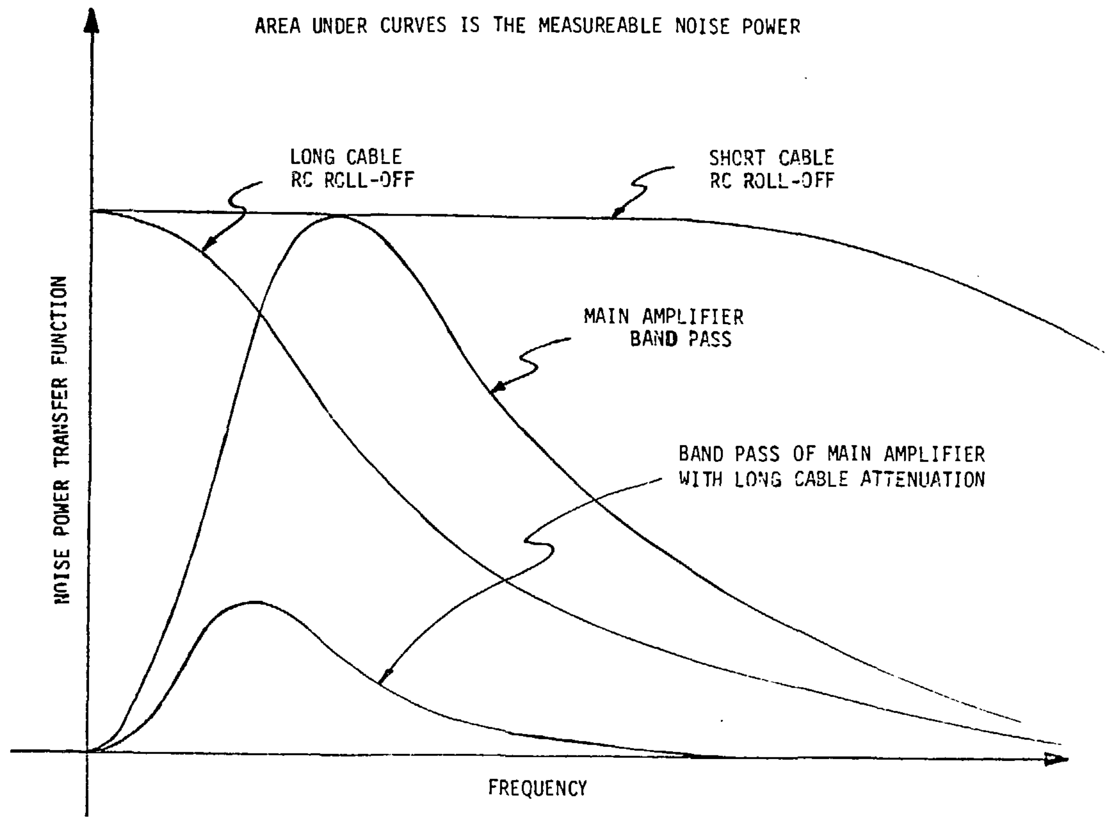


Figure 4

GROUNDING & SHIELDING OF RTDs INSTALLED IN CYAP - LOOP 4

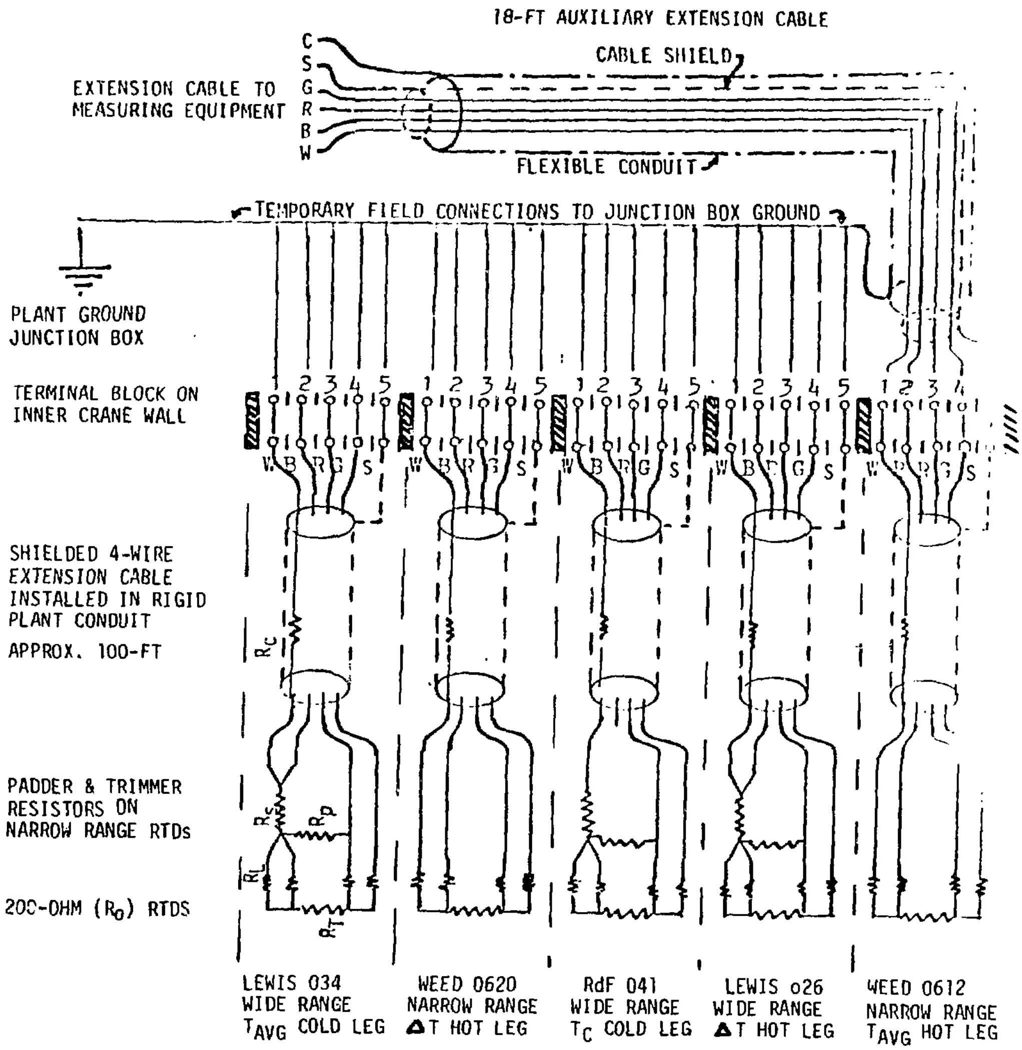


Table 1

METHODS FOR MEASURING LENGTH OF INSTALLED EXTENSION CABLES

FOR ~100 FT CYAP CABLE

Measured Quantity	Measuring Instrument	Limitations	Effective Frequency	Length Uncertainty
DC RESISTANCE	DC BRIDGE	TEMPERATURE DEPENDENT INCLUDES INTERNAL LEAD RESISTANCE (R_L)	0 Hz	±3.1%
INPUT IMPEDANCE PHASE MINIMUM	SPECTRAL ANALYZER TEKTRONICX MODEL 7L5	SENSITIVE TO CABLE LAYOUT, CONDUIT AND INDUCTANCE AT HIGH FREQUENCIES	~1 MHz	±1.4%
PROPAGATION VELOCITY LENGTH	TIME DOMAIN REFLECTOMETER TEK MODEL 1502	LACK OF RESOLUTION; EFFECT OF CABLE CABLE TERMINATION	>1 MHz	±2.0%
LOOP-TO-SHIELD CAPACITANCE	LOW IMPEDANCE ANALYZER HP MODEL 4192A	RELATED TO ACTUAL CASE FOR NOISE MEASUREMENTS, BUT AFFECTED BY WIRE LAY IN CABLE	OVER PASSBAND USED IN NOISE MEASUREMENTS	±0.6%
SHORTED LOOP-TO-SHORTED LOOP CAPACITANCE (JNPT CONNECTION)	LOW IMPEDANCE ANALYZER HP MODEL 4192A	CAPACITANCE VALUE SLIGHTLY AFFECTED BY TERMINATION RESISTANCE	OVER PASSBAND USED IN NOISE MEASUREMENTS	±0.5%

temperatures was 0.04% or 0.43°F at a normal operating temperature of 585°F, and 0.16% or 0.94°F at shutdown. These results listed in Table 2 are well within the calculated overall measurement uncertainty of 0.2% rms, using direct measurement of the cable transfer function.

Conclusion and Assessment

Methods have been demonstrated in operating nuclear plants for the in situ calibration of resistance thermometers with agreement between measured noise temperatures and dc calibration temperatures well within these required by the plant. A comparison of the results of Johnson noise power testing results and uncertainties, the requirements for accuracy, and PRT calibration tolerances is shown in Figure 5. The methods use Johnson noise measurements and provide an absolute calibration independent of the prior dc calibration. The methods include techniques for characterization of the installed extension cables and the quantitative determination of induced EMI and its effect on the calibration. The techniques are applicable to ordinary 4-wire platinum resistance thermometers operating over their entire design temperature range and to extension cables of about 100 ft length. Careful attention needs to be paid to the choice of cables, location of terminal boxes, and grounding and shielding practices in the plant installation to achieve comparable results.

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Table 2. *Test Result Summary of In Situ Calibration of PRTs Installed in CYAP*

	DC Calibration			JNPT Noise Measurement					
				Similitude Method			Direct Cable Measurement		
	Resistance	Temperature		Resistance	Temperature		Resistance	Temperature	
	ohms	°F	K	ohms	°F	K	ohms	°F	K
Full Power Tests (Test III - December 1983:									
Value	433.54	584.69	580.20	437.60	589.39	582.81	436.80	585.12	580.44
Difference				+ 4.06	+ 4.7	+ 2.6	+ 3.26	+ 0.43	+ 0.24
% Difference				+ 0.69%		+ 0.45%	+ 0.43		+ 0.04%
% Uncertainty						± 0.4 %			± 0.2 %
Shut Down Tests (Test II - July 1984)									
Value	236.148	113.05	318.18	238.33	112.48	317.86	237.04	113.99	318.70
Difference				+ 2.18	- 0.57	- 0.32	+ 0.90	+ 0.94	+ 0.53
% Difference				+ 0.93%		- 0.10%	+ 0.38%		+ 0.17%
% Uncertainty						± 0.4 %			± 0.2 %

Figure 5.

RTD ACCURACY UNCERTAINTY USING JOHNSON NOISE POWER IN-SITU CALIBRATION