# SELF-HEATING, GAMMA HEATING AND HEAT LOSS EFFECTS ON RESISTANCE TEMPERATURE DETECTOR (RTD) ACCURACY[1]

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## ABSTRACT

Resistance temperature detectors (RTDs) are extensively used in CANDU®[2] nuclear power stations for measuring various process and equipment temperatures. Accuracy of measurement is an important performance parameter of RTDs and has great impact on the thermal power efficiency and safety of the plant.

There are a number of factors that contribute to some extent to RTD measurement error. Self-heating, gamma heating and the heat-loss through conduction of the thermowell are three of these factors. The degree to which these three affect accuracy of RTDs used for the measurement of reactor inlet header temperature (RIHT) has been analyzed and is presented in this paper.

## 1. INTRODUCTION

Resistance temperature detectors (RTDs) are extensively used in CANDU power reactors to measure various process and equipment temperatures. Accuracy and response-time are the two key RTD performance parameters. For steady-state temperature measurement, the major concerns are the accuracy and stability of the measurement. For dynamic temperature measurement, there is also a requirement that the response-time of the RTD measurement be fast enough [1, 2].

The accuracy of the RTD measurement at some locations in the reactor directly affects the efficiency of reactor power generation. One such location is the reactor inlet header temperature (RIHT) measurement. The upper limit of the reactor inlet header temperature is one of the parameters that affects critical heat flux in the fuel channel and the integrity of the fuel. This is a nuclear safety limit that cannot be exceeded. An increase in the accuracy of the RIHT measurement means a reduction in the allowance for the instrument error included in the limit. This will allow the RIHT to be closer to the limit and will result in an increase in reactor power output. For example, the reactor thermal power output is calculated based on measurements of temperature difference, $\Delta T$, between the outlets and the inlets of the reactor primary heat transport system, the flows of the coolant, and on the derived exit quality (the steam content) of the coolant. Since $\Delta T$ is less than 50 °C, an improvement of only 1°C can mean about 2% increase in reactor power output, and a significant increase in generating revenue. Consequently, accurate measurement of $\Delta T$ with a minimum margin of uncertainty is a very desirable goal. It was calculated that an increase of RIHT by 1°C would increase the boiler pressure by 83

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[1] AECL-11874, COG-97-437-I

[2] CANDU® is a registered trademark of Atomic Energy Canada Limited (AECL).

kPa, which could increase the output by 15 MW per unit [3]. A study of various factors that affect the accuracy of RIHT measurement was conducted by BNGS and NTS staff [4, 5]. This paper describes a companion study on three factors that limit accuracy: self-heating, gamma heating, and conductive heat loss through thermowell that houses the RTD [6].

The paper is organized as follows: Section 2 introduces how self-heating affects temperature measurement, the limitation of an estimate of RTD self-heating based on manufacturer specification, and a method of measuring self-heating index in-situ for calculating the self-heating error of RTDs in operating condition. Section 3 describes the error caused by gamma heating and an estimate of gamma heating effect on RIHT based on the known maximum gamma field and the mass of the thermowell. Section 4 describes how conductive heat loss will affect accuracy of temperature measurement and provides a calculation of conductive heat loss in the RIHT case. Section 5 concludes the paper.

## 2. SELF-HEATING

The resistance of an RTD varies almost linearly with the temperature it measures. Therefore it is possible to measure the temperature by measuring the resistance of the RTD. The relationship of resistance with respect to temperature of industrial RTDs is specified in various standards including IEC standard 751 [7].

Measurement of RTD resistance requires a current through the RTD. This current $I$, though small, will produce Joule heating proportional to $I^2R$ in an RTD of resistance $R$, and result in a temperature error. To reduce this so-called "self-heating" error, one needs to reduce the current: the smaller the current, the smaller the self-heating error. However, there is a lower limit in current because of other considerations such as noise problems, and signal-to-noise ratios. The RTD standard recommends that the current used to measure steady-state resistance of an RTD be small enough to limit the power dissipation in the RTD to not more than 0.1 mW [7].

The self-heating index (SHI) is an RTD self-heating characteristics normally supplied by manufacturers. The SHI is the ratio of resistance changes (in ohms) to unit electric power generated in the RTD sensing element (in mW) as the result of application of electric current. Sometimes the SHI is expressed as the reciprocal, i.e., the electrical power needed for unit resistance change. It may also be expressed as temperature changes (as opposed to resistance change) per unit electric power generated in the RTD, since the relationship between temperature and resistance has been well defined in standards. Based on the SHI the self-heating error can be calculated for an RTD for a given current. An example is given below.

The SHI for Rosemount model 104-1584 RTD is given as 25 mW/ °C for a bare RTD [8], which means that every 25 mW electric power dissipated in the RTD will result in a + 1 °C error in RTD output.

As provided in RTD resistance table in [7], the RTD resistance $R_t$ at 250 °C is:

$$R_t = 194.10\Omega \tag{1}$$

If a 7 mA current, $I_t$, is applied, then the voltage across the RTD is:

$$\begin{aligned} V_t &= R_t * I_t = 194.10 * 0.007 \\ &= 1.3587V \approx 1.4V \end{aligned} \tag{2}$$

The power $P_t$ dissipated in the RTD is:

$$P_t = V_t * I_t = 1.4 * 0.007$$
$$= 0.0098W = 9.8mW \tag{3}$$

From the SHI specification of 25mW/ °C and the operating temperature, the temperature over-estimate error is about +0.4 °C.

There are several limitations in estimating self-heating error based on the manufacturer-supplied SHI. One limitation is that the specification supplied is for bare RTDs not for RTDs housed in thermowells (see Section 4 for description of a thermowell), which are common in a nuclear power reactor. More importantly, the manufacturer's SHI is determined at room-temperature in water flowing at 1 m/s, whereas the RIHT RTDs are working at a much higher temperature and flow rate. Also in CANDU, the thermowell is often immersed in heavy water which has a different thermodynamic property than light water. Though standard methods such as that given in IEC Standard 751 are used to measure the SHI, the standard method, like the one used by the manufacturer, is specified for specific temperature and flow conditions (an ice bath in IEC 751) only. Consequently, the +0.4 °C error estimate above is condition-dependent and cannot be used as a correction to the RTD output.

As mentioned above, self-heating error would result when RTDs are calibrated in one environment and used in another environment. For example, RTDs calibrated in an oil bath and subsequently used in flowing water may have significantly different SHIs [9]. Therefore the best way to determine the self-heating error is to measure the SHI with the RTD in-situ. A procedure for measuring in-situ SHI is given below based on an earlier EPRI report [10]. The procedure is based on steady state measurement. Currents of different strength are injected into the RTD and the steady-state resistance (and hence, temperature) due to these currents are measured as follow:

(1) Increase the RTD current incrementally from 1-6 mA to 20-60 mA.
(2) Measure the RTD resistance when steady state is attained after each increment in current.
(3) Calculate the amount of power generated in the sensor from:
$$P = I^2R$$
(4) Plot the values of resistance as a function of electric power dissipated in the RTD (*R* vs. *P*).

A typical plot would show a straight line such as that shown in Figure 1 [10]. The slope of the line, i.e., $\Delta R/\Delta Q$, is the SHI at the operating temperature. It was reported that the value of SHI was quite different from one RTD to another, even when they were the same design [10]. This proves the thermodynamic condition dependence of the SHI. Therefore, the SHI of one RTD should not be used to specify another RTD of the same type at a different location or under different conditions. However, if the SHI can be correctly measured in situ for a particular condition, the RTD error due to self-heating for that particular condition can be accounted for.

## 3. GAMMA HEATING

When an RTD and a thermowell are exposed to a gamma field, they will absorb some of the energy carried by the gamma radiation. Gamma rays are a high energy form of electromagnetic waves. Their interactions with other materials basically are in three ways: photoelectric effect, Compton scattering and pair production. The interactions cause the temperature of the RTD assembly to increase. This will cause the RTD measurement to read higher than the actual ambient temperature it is measuring.

The approach used in estimating the bound of RTD measurement error caused by gamma heating is based on the knowledge of the gamma field and the mass of the RTD assembly. In CANDU, the headers and feeders are shielded from the accessible areas of the reactor building by the concrete walls and roof of the fueling machine vault. Inside the vault, these components give rise to gamma fields as high as 1 Gy/h=100 R/h.

$$1\frac{Gy}{h} = 1\frac{J/kg}{h} = \frac{1}{3600}\frac{J}{s \cdot kg} = 0.000278\frac{W}{kg} \tag{4}$$

This value can be used to estimate a bound of the gamma heating on the thermowell (the mass of RTD is small relative to the thermowell and can be neglected).

Assuming the mass of the thermowell is 3 kg and all gamma energy is deposited in the thermowell without heat-loss, then the heating power is:

$$0.000278\frac{W}{kg} * 3kg = 0.00083W = 0.83mW \tag{5}$$

Therefore, the energy due to gamma heating is less than one-tenth of the energy of the estimated RTD self-heating. Thus the temperature error due to gamma heating can be neglected.

## 4. HEAT LOSS THROUGH THE THERMOWELL

The RTD thermowell is a protective jacket used to isolate the RTD from the process fluid and to permit easy replacement of the RTD. The measurement of a fluid temperature by an RTD placed in a thermowell could introduce errors due to conductive heat loss through the thermowell, if proper consideration was not given in the initial design. This heat-loss error is sometimes referred to as stem loss [9].

The mathematical expression of the error caused by conductive heat-loss through the thermowell can be found in standard heat transfer texts. The authors re-derived the equation using two assumed boundary conditions: (1) at the pipe wall, the temperature difference is that between the ambient temperature and the fluid temperature inside the pipe, and (2) at the RTD end of the thermowell, there is zero temperature gradient with distance along the thermowell. The difference in temperature between the fluid and the well near the point at which the RTD is located represents the approximate error due to heat loss through conduction from the thermowell. The temperature error, $T_e$, may be expressed as [12]:

$$T_e = \frac{T_w}{\cosh(ML)} \tag{6}$$

where

$T_w$ = temperature difference between the header pipe wall (in which the well is inserted) and the fluid, °C.

$L$ = length of the well in m, and

$M = (f \pi D/kA)^{1/2}$, $m^{-1}$ (7)

f = film conductance from the side wall of the well to the fluid, $W/m^2 K$.

D = outside diameter of the well, m.

k = thermal conductivity of the well, W/m K.

A = cross sectional area of walls of the well, $m^2$.

To solve equations (6) and (7), it is necessary to obtain the film conductance f. In heat transfer theory [13], f in units of $W/m^2K$ can be calculated using,

$$f = \frac{Nu\ k}{D}, \qquad (8)$$

where Nu is the Nusselt number, k is thermal conductivity of the fluid, and D is the well diameter. The Nusselt number can be expressed as:

$$Nu = a\,Re^b\,Pr^c, \qquad (9)$$

where a, b, c are constants, Re is the Reynolds number and Pr is the Prandtl number. Note that the Reynolds number and the Prandtl number are unitless numbers given by:

$$Re = \frac{GD}{\mu} \qquad (10)$$

$$Pr = \frac{c_p\mu}{k} \qquad (11)$$

where

G = flow per unit area, $kg/m^2 s$.

$\mu$ = dynamic viscosity of the fluid, Pa s.

$c_p$ = specific heat of the fluid, J / kg K.

k = thermal conductivity of the fluid, W/m K.

Substituting (9), (10) and (11) in (8), the film conductance can be expressed as:

$$f = \frac{ak}{D}\left(\frac{GD}{\mu}\right)^b\left(\frac{c_p\mu}{k}\right)^c, \qquad (12)$$

Note that there are a number of choices for the constants a, b, c. There seems to be no absolute method to choose these constants in the literature. Generally the practice is to use a few commonly used groups according to the range of the calculated Reynolds number.

The inner zone RIH size and operational conditions are used for calculating (6), (7), (12). The thermodynamic properties of heavy water are also used in calculating the film conductance.

From these data, the total flow for each inner zone inlet header and the unit area flow are calculated. The detailed calculation can be found in [6]. The Reynolds number, the Prandtl number and the ratio k/D are thus obtained. The group of constants a, b, c in (12) were taken from Table 12.1 in [13] for the closest Reynolds number range.

The film conductance can thus be calculated from (8).

For different lengths of the thermowell, the calculated values of mL, cosh(mL) and $T_e/T_w$ are listed in Table 1.

The maximum $T_w$ (the difference of ambient and the fluid temperature) is estimated to be $T_w$ = 253 °C - 20 °C = 233 °C assuming the ambient temperature is 20 °C (the actual ambient temperature is much higher than this due to the insulation of the header and feeder cabinet). From the last column of Table 1 we can see that the error $T_e$ is phenomenally small even with the maximum possible $T_w$.

This may be because the assumed boundary conditions do not exactly conform to the real situation, especially if the thermowell is not long relative to its diameter. However, the conclusion that the error due to heat loss through conduction along the thermowell is negligible, is supported by calculation using a different method (see page 244 of [13]).

## 5. CONCLUSIONS

The self-heating of the RTD will cause the RTD to read high. This error is in the safe direction but there is a production penalty. The estimated self-heating error for a bare sensor is +0.4 °C using the self-heating index given in manufacturer's specification and the BNGS RIH operating temperature. A standard method such as IEC 751 may be used to measure the self-heating index (SHI). However, the standard method, like the one used by the manufacturer, is specified for a specific temperature and flow condition only. The self-heating index is heat-transfer-condition dependent. Consequently, the +0.4 °C error estimate is condition-dependent and cannot be used as a correction to the RTD output as a means of reducing production penalty. A procedure that can be used to determine in-situ SHI is given. By substituting the actual electric power applied to the RTD into SHI, the measurement error caused by the self-heating effect can be determined at operating conditions and could be accounted for.

The bound of error caused by gamma heating was estimated using known gamma field and the mass of the RTD assembly and it is concluded that gamma heating of the thermowell causes a negligible error.

The heat loss through the thermowell conduction was also found to be negligible.

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Table 1. The calculated values of mL, cosh(mL) and $T_e/T_w$ for different length of thermowells

| **L (m)** | **mL** | **cosh(mL)** | **$T_e/T_w$ = 1/cosh(mL)** |
|---|---|---|---|
| 2” = .0508 m | 33.22 | 1.3373 e 14 | 0.7478 e - 14 |
| 4” = .1016 m | 66.45 | 3.6128 e 28 | 0.2768 e - 28 |
| 6” = .1524 m | 99.67 | 9.6628 e 42 | 0.1035 e - 42 |

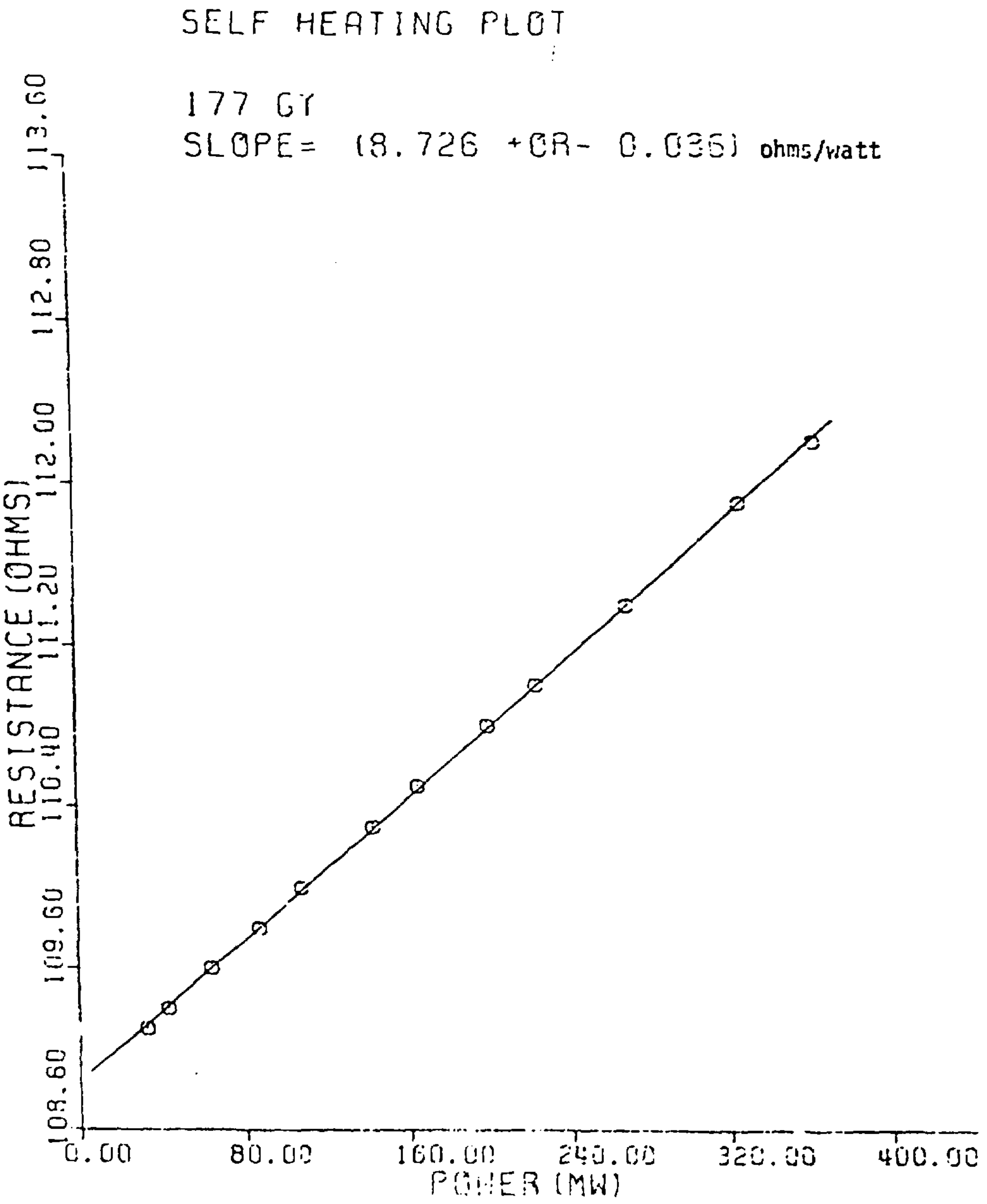

Figure 1. Typical Plot of Self-Heating Index Measurement