POWER RAISE THROUGH IMPROVED REACTOR INLET HEADER TEMPERATURE MEASUREMENT AT BRUCE A NUCLEAR GENERATING STATION

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SUMMARY

For optimal performance, CANDU reactors are operated within a small reactor inlet header (RIH) temperature range during normal operation. The upper limit on reactor inlet header temperature is one of several parameters which affects critical heat flux in the reactor channel, and hence the integrity of the fuel. This limit, including an allowance for instrument accuracy, is a nuclear safety requirement which cannot be exceeded. As the boilers and feedwater pre-heaters have aged they have become less efficient at removing heat. The boiler primary side divider plate may also be allowing some inlet-to-outlet bypass flow on the primary heat transport (D_2O) side. Over time this has caused the boiler outlet temperature and the reactor inlet temperature to slowly rise.

At present the Bruce A units are de-rated to compensate for the increased RIH temperature. A more accurate temperature measurement would reduce the uncertainty allowance in the safety analysis and allow the station to raise the RIH temperature to a value closer to the safety limit. Hence, it could increase the plant power output and, therefore the plant's revenue. Based on the present operating state of the Bruce A units, increasing the RIH temperature by 1°C would increase the Boiler Pressure 83 kPa, which could increase the output by 15 MW per unit.

Currently, the nominal RIH temperature is 250°C, and includes an inaccuracy of as much as ±3 °C. This inaccuracy is made up of process flow stratification, instrument tolerances and drift, and environmental effects. A detailed analysis of the measurement loop errors was performed and it was demonstrated that by using commercially available digital technology, the measurement loop error can be reduced to ±0.72°C. This could result in an improvement of 2.28°C or 34 MW per unit.

The use of calibrated high quality dual element RTD's (Resistance Temperature Detectors) installed in the existing spare thermowells provides redundancy at low cost. Using different transmitter manufacturers on opposite legs of the RTD temperature measurement loop provides diversity in measurement and permits the use of commercially available 'smart' digital transmitters at no extra significant cost or safety impact.

1. INTRODUCTION

Reactor Inlet Header (RIH) temperature has become a factor limiting the performance of the Ontario Hydro Bruce A units. Specifically, the RIH temperature is one of several parameters that is preventing the Bruce A units from returning to 94% power operation.

RIH temperature is one of several parameters which affect the critical heat flux in the reactor channel, and hence the integrity of the fuel. Ideally, RIH temperature should be lowered, but this cannot be done without improving the heat transfer performance of the boilers and feedwater pre-heaters. Unfortunately, the physical performance of the boilers and pre-heaters has decayed and continues to decay over time, and as a result the RIH temperature has been rising and approaching its defined limit.

At reduced reactor power levels, the RIH temperature has been controlled by lowering the boiler (secondary side) pressure, which lowers the RIH temperature by increasing the heat transfer rate. But lowering the boiler pressure will also limit the turbine power output capacity; as the boiler pressure goes down so does the turbine capacity, below 94%.

In order to raise the unit power output, a solution to the rising RIH temperature problem must be found. The long term solution to this problem will be improvement of the boiler and preheater performance, which to date has not been achieved, but work continues on this issue. In the short term, more accurately defining the actual RIH temperature limit and/or reducing the measurement uncertainty (error) incorporated in the operating margin would allow improvements in unit performance.

The remainder of this paper deals with methods of reducing the measurement uncertainty. It is recognized that even small improvements in measurement accuracy will allow the unit to operate closer to the true RIH temperature limit. Based on the present operating state of the units, even a 1°C improvement in RIH temperature measurement would allow boiler pressure to increase 83 kPa, which can correspond to approximately 15 MW output power improvement.

To reduce the measurement error, an understanding of the following items is essential:

- Reactor Inlet Header design and processes affecting the temperature measurement,
- existing measurement loop and location,
- measurement loop errors sources, and
- the quantification of the errors in the measurement loop.

With an understanding of the current RIH temperature measurement loop and methods available to improve it, a solution to reduce the measurement uncertainty is presented.

2. RIH DESIGN

Four (4) Reactor Inlet Headers form part of the CANDU system Primary Heat Transport (PHT) system. There are two (2) Outer Zone Inlet Headers (ROZIH) and two (2) Inner Zone Inlet Headers (RIZIH). There is one RIZIH and one ROZIH at each end of the reactor core, (see figure 1). There are also 2 Reactor Outlet Headers, again one at each end.

The PHT is a closed circulating system; the flow is from the Reactor Inlet Headers through the reactor to the Outlet Header, and on to the PHT pumps that maintain the flow. From the PHT pumps the flow splits into 3 paths; one path to the ROZIH, one path bypasses the preheater, and one path through the preheater. From the preheater the flow is mixed with the bypass flow, and then proceeds to the RIZIH. Note that the preheater actually cools the PHT side and warms the secondary side.

The headers are enclosed in feeder cabinets. These cabinets are essentially constructed as small, well insulated rooms around both the inlet and outlet headers. The flow enters the inlet headers from both ends, and therefore splits the headers in half, which results in a quadrant arrangement, (NW, NE, SW, SE). Specifically, it must be assumed that each end of a given header will be at a slightly different temperature. For convenience the header temperature can be referred to by header and quadrant, (e.g. NE RIZIH would refer to the North end temperature of the East Reactor Inner Zone Inlet Header.).

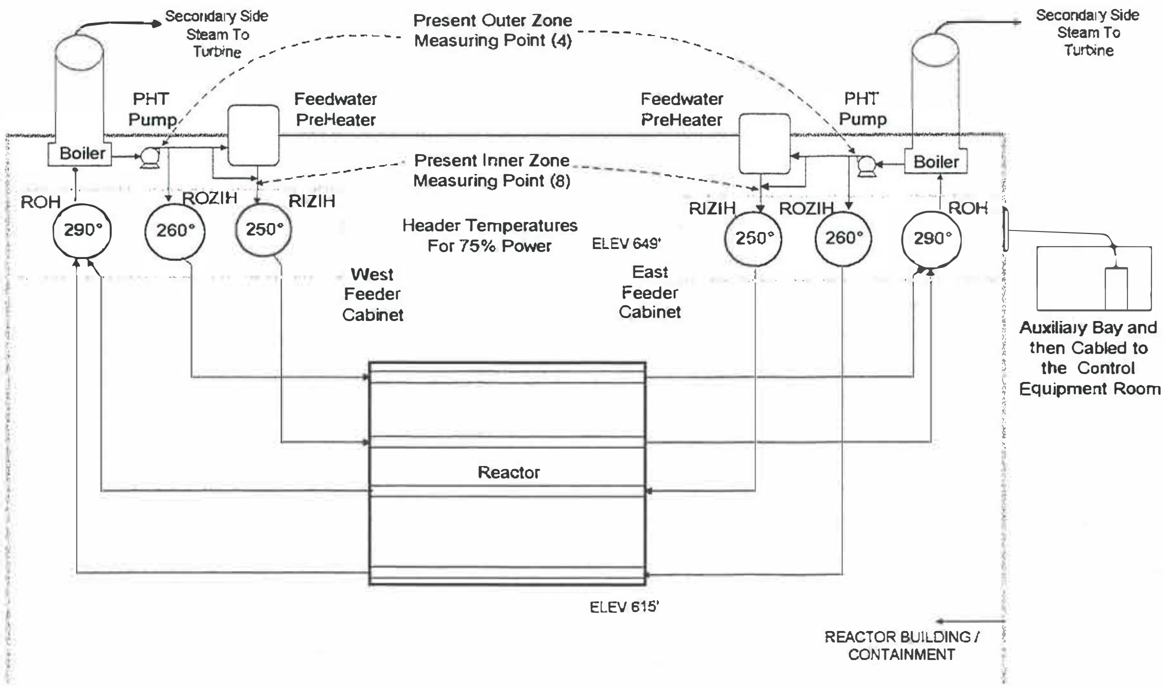

Figure 1 Reactor Header Simplified General Arrangement

Of particular interest is the location of the Inner Zone measuring point, (see Figure 2). It is located near the junction of two (2) flow streams; the preheater outlet and the preheater bypass flows. According to pipe fluid mechanics the complete mixing of two fluid streams will not occur for at least 2 pipe diameters from the junction. Incomplete mixing will skew the temperature measurement, either high or low depending on which flow stream is dominant.

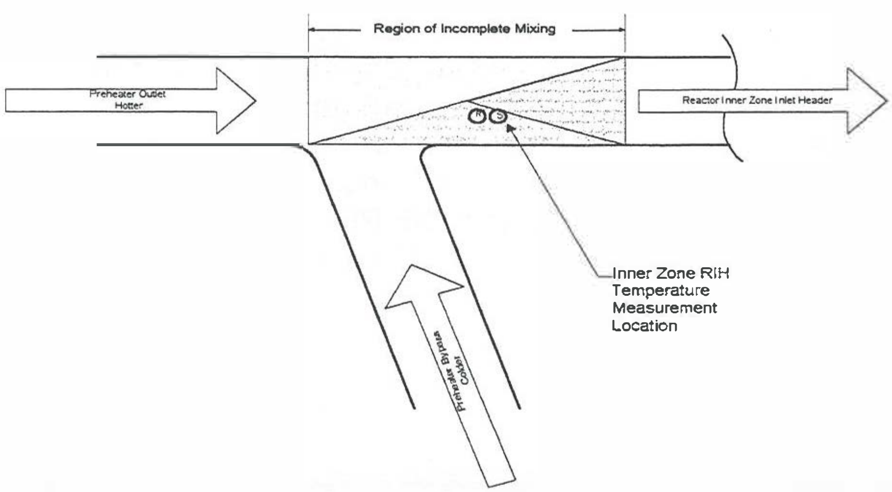

Figure 2 Relative Location of Inner Zone RIH Temperature Measurement

2.1 RIH Temperature Effects on Power Raise

In the simplest terms, the Reactor and the associated primary heat transport system must work in concert with the secondary heat transport system. The heat generated in the Reactor must be removed by the primary heat transport system and transferred, via the Boiler and pre-heaters, to the Secondary side. Assuming that the PHT pressure is constant and that the Reactor Outlet temperature is fixed (at saturation), the only things that will affect the RIH temperature are the boiler and preheater heat transfer rates.

To lower the RIH temperature, the Primary to Secondary side heat transfer rate must increase. This is done by lowering the secondary side boiler pressure [i]. A continued decrease of the Boiler Pressure will directly limit the Turbine Generator capacity, which requires pressure to produce power. To date this has not been a problem as the units have operated at reduced capacity, and the turbine governor valves have had room to operate. But at increased power with decreased pressure, the governor valves will be required to be full open and beyond their capacity.

3. PRESENT MEASUREMENT LOOP

The RIH temperature is measured (see Figure 3) using standard interchangeable Resistance Temperature Detectors (RTD's). The resistance of an RTD increases as the temperature rises. The variable resistance is converted to a voltage signal using an interchangeable Wheatstone Bridge circuit. The voltage signal is converted to a digital value via a Analog to Digital (A/D) converter at the computer. The digital value is then converted into a temperature using a standard equation for each RTD type.

There are twelve (12) RTD's located at eight (8) present locations. There is one 4" deep thermowell located at each of the four (4) heat transport pump discharges used to measure the ROZIH temperature. And, two 4" deep thermowells located at each end of the two RIZIH. These presently provide a measurement of both inner and outer zone temperatures for each quadrant.

In addition to the above existing RTD's, there are three (3) spare 6" deep thermowells available in each of the four inlet headers. These are the proposed thermowell locations referred to in the remainder of this paper.

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[i] As a reference the original plant design was based on 4450 kPa Boiler pressure; Bruce A Unit 3 is currently (spring 1997) operating at or near 3850 kPa.

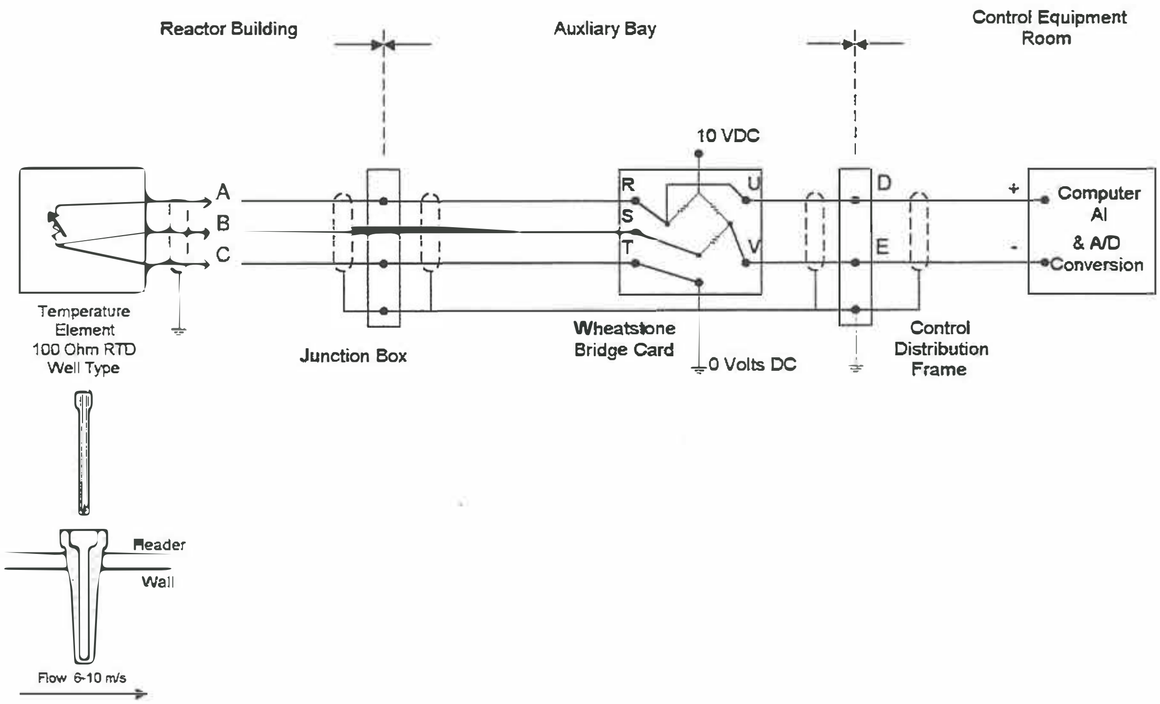

Figure 3 Present RTD Measurement Loop - Simplified

As can be seen in Figure 3, there are three (3) physically distinct parts, to the measurement loop:

- the RTD in the Reactor Building; from the thermowell to the Junction Box,
- the Wheatstone Bridge in the Auxiliary Bay; from the Junction Box to the Control Distribution Frame, and
- the computer in the Control Equipment Room; from the Control Distribution Frame to the computer.

Each of these parts has a different physical environment but are connected using standard shielded cable as shown.

3.1 Environmental Conditions

The environmental conditions associated with each part of the measurement loop vary significantly and will affect the accuracy of the measurement loop.

In the Reactor Building and specifically within the feeder cabinet, the environmental conditions (design) and radiation levels are:

- Temperature — ambient to 350°C
- Humidity — 0-95%
- Radiation 75% full power — Gamma, 80 Rad/h
- Radiation 95% full power — Gamma, 100 Rad/h
- Radiation — Slow Neutron, equivalent to 0.7-1 Rad/h

In the Auxiliary equipment bay, the environmental conditions are:

- Temperature — 10°C to 40°C, (normal operation)
- Humidity — 20-95%

In the Computer Room and Control Equipment Room, the environmental conditions are:

- Temperature — 10-40°C
- Humidity — 20-95%

3.2 Measurement Loop Errors

The following section is a review of 17 identified RTD measurement loop errors, their sources and the methods available to reduce them. The effects of these errors are summarized at the end of this section, in Table 1.

3.2.1 Reactor Building Environmental Effects

Gamma Ray Heating Gamma radiation can cause a thermocouple or RTD to read falsely high. This is due to the physical heating of the temperature element itself. At full reactor power the In-Core gamma field is 200Mrad/h which would cause a heating effect[1] of 5W/cm^3 which, in turn, would cause the readings to be 14°C higher.

As the RIH RTD's are not exposed to the same magnitude of radiation this effect is not expected to be as large. Assuming the RIH's are only exposed to 100rad/h of gamma radiation and assuming a linear relationship with radiation level, the average effect would be 0.000007°C. Although the physical RTD designs are not the same, (i.e. heat transfer co-efficient and physical volumes of the In-Core RTD's versus RIH temperature RTD's). The gamma radiation heating was confirmed to be 'negligible' as part of a CANDU Owners Group (COG) study.

Transmutation causes a change in the atomic structure of the sensing element, causing the RTD to have a different resistance versus temperature characteristic. This change may appear as a temperature drift with time, or as an erratic measurement. Transmutation is caused by the absorption of neutrons within the atomic nucleus of the material used, i.e. neutron capture. The effects of transmutation are typically irreversible. They can be identified by reviewing the calibration history or by comparison with new RTD's of a similar design in the same location.

A calibration comparison of 15 stocked RTD's versus 9 used RTD's removed from Unit 2 Bruce A after 19 years of service, was made. The results of this comparison indicated no significant difference between the Stock RTD's and the Used RTD's measured resistance over the full operating temperature range (0-320°C). Neither was there a significant drift from the manufacturer's stated temperature versus resistance curve, as shown by the results of the calibration check.

The calibration errors for each RTD were summed over a span of 0-320°C and a "mean" error calculated. For the 9 Used RTD's the average of the "mean" errors was -0.05Ω with a standard deviation of ±0.06 Ω. Similarly the average of the "mean" errors of the Stock RTD's was +0.02Ω with a standard deviation of ±0.06 Ω. This implies a systematic error of -0.07Ω, (-0.05 to +0.02 Ω), with a random component of ±0.06 Ω for the Used RTD's versus the Stock RTD's. This translates to only -0.027°C ±0.024°C, over 19 years. Note test errors are well within the manufacturer's specified tolerances of ±1.5°C, therefore the error component due to transmutation is not readily apparent. The above errors are more likely to be related to their 19 years of service, but have been included for completeness.

<u>Aging or Drift</u> or refers to the degradation of the RTD's performance from its calibrated value with time in a normal operating environment, under normal conditions. The normal environmental stressors that an RTD will be exposed to include humidity, heat, vibration, radiation, temperature cycling. One or more of these stressors is always acting on the RTD whether it is in stock or is installed.

Results of aging tests performed by the US Nuclear Regulatory Commission (reference 2 section 12, which excludes radiation), showed that after a burn-in period of 6 months, nuclear grade RTD drift tended to stabilize in a drift band of ±0.2°C. Aging tests on commercial grade RTD's showed twice the drift for similar testing, i.e. ±0.4°C. These results are valid for the nuclear grade RTD's that survived the aging test, (63%). During the aging test 17% failed with open circuits, which were easily detected, while 20% showed a drift between 0.6-3.0°C, which were harder to detect in the absence of a reference against which to measure the drift.

<u>Radiation Induced Currents</u> are likely to result from a flow of electrons between the core wires and the outer sheath of the RTD cable, due to ionization of the cable materials by nuclear interactions (reference 1). These effects were not

observed during In-Core temperature monitoring, but that may be attributed to good design.

If radiation induced currents exist, they can be identified by measuring the variations in bridge output when the RTD is irradiated and when it is not. If a change is observed, it will be systematic and a function of radiation level which in turn is a function of reactor power level. No distinguishable radiation induced currents have been observed.

Insulation Dielectric of both the cable and RTD, is affected by moisture and radiation. Reducing the insulation dielectric will allow current leakage to ground, which will have the effect of lowering the current to the bridge, and hence a lower temperature reading. The present RTD specification requires that the resistance between the leadwire and the sheath (or ground) should be at least 1000MΩ at room temperature and no less than 50 MΩ at 312°C. As an example, lowering the insulation resistance to 1MΩ will cause an error of 0.019°C at 300°C. This would result in a systematic negative error.

Higher levels of radiation reduce the insulation resistance of the RTD ceramic and oxide insulators while the radiation exists, so that a current leakage could occur between the signal wires and the RTD sheath. This phenomenon has been observed when measurements were taken in areas of intense radiation, e.g. during In-Core measurements where insulation resistance can drop by about 1 MΩ at full reactor power, (reference 1). As the radiation fields in the location of the RIH RTD's are orders of magnitude less than that observed during the In-Core measurement, we can assume that the radiation short-term effects on the Insulation Dielectric are negligible. After years of operation, the accumulated radiation dose is brittling on the wire outer insulation and terminal block material so that they disintegrate when touched. Presently there is a program in place to repair the terminal blocks and cabling as part of regular maintenance.

3.2.2 Reactor Building Installation Effects

Stem losses are caused by large temperature gradients along the RTD stem which will cause the RTD to indicate a temperature lower than the actual process. The effect of stem losses was quantified by the US Nuclear Regulatory Commission, (reference 2) and varies as a function of the relative RTD immersion length, the temperature gradient and amount of insulation present. But provided that more than 25% of the RTD is immersed, the stem loss error will be << 0.01°C.

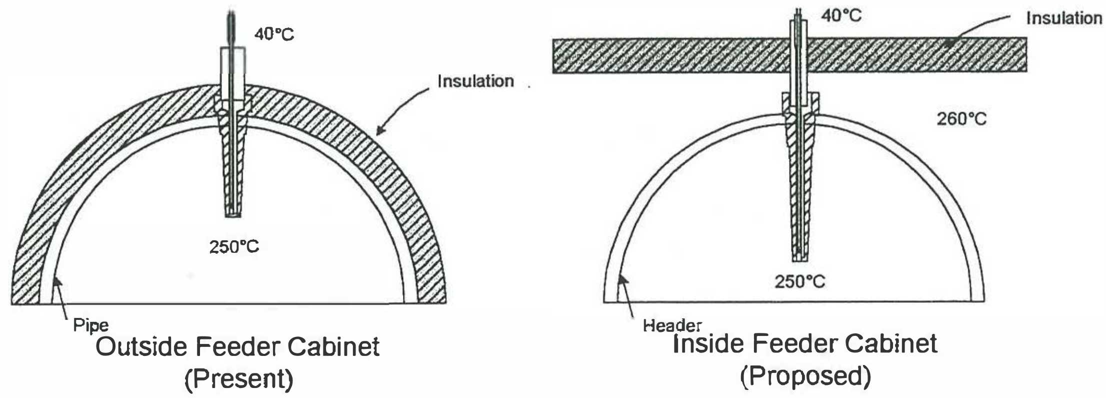

Figure 4 Insulation Arrangement

The present measurement points (see Figure 4) are located **outside** the feeder cabinets in 4" thermowells, inside well insulated piping. The RTD's themselves are approximately 10" in length. Therefore the current RTD's are immersed at least 40%, this will result in a negligible error, << 0.01°C.

The proposed thermowells are located **inside** the feeder cabinet, and are not directly insulated. The thermowells are 6" deep. The proposed RTD's are at least 36" long, resulting in 17% immersion. However, since both the Inlet and Outlet headers are located within the same feeder cabinet and neither is insulated, the ambient cabinet conditions will tend to average slightly hotter (5-10°C) than the actual RIH temperature, so the portion to the RTD stem inside the feeder cabinet can be considered part of the immersed length, effectively doubling the immersion to 34%, this will result in a negligible error, << 0.01°C. The guide-tube is metallic and is considered part of the thermowell, (as seen in Figure 4).

Thermoelectric errors result if dissimilar metals in the RTD circuit are at different temperatures, (e.g. the extension leads). The resulting voltage may interfere with the resistance measurement and can cause as much as a 0.5°C error, (reference 2). This will be a systematic error which will vary with the temperature difference between the RTD wires and their extension wires. It is most likely to occur in the lead wires that run from the RTD to outside the feeder cabinet, resulting in a temperature gradient of up to 250°C. This error can be detected by measuring the voltage across the RTD leads, and then reversing the leads and re-measuring the voltage. If the results are different thermoelectric errors may be present in the RTD measurement loop. The effect has not been distinguishable in the results to-date, and therefore no error was assigned.

Thermoelectric errors can be reduced to insignificance if the extension wires/cables are made of platinum similar to the RTD's. However, this is impractical. A 4-wire RTD and bridge circuit could also be used to achieve the same result.

RTD - Thermowell Contact effects the RTD response time, (reference 2, section 24). Spring Loaded Bayonet type RTD's are used in both the present and proposed locations. Both the present and the proposed RTD's and thermowells are flat bottom, with straight insertion. The RTD spring is designed to provide a setting force of 8 lb., in the installed position. This setup ensures that good thermal contact is maintained for the service life of the RTD. As well the RTD and thermowell are made of corrosion resistant stainless steel. No error is assigned to this factor.

Handling and Hysteresis Errors may result if an RTD has been mishandled, dropped, bent, etc. Thermal hysteresis will cause the resistance to be different for a given temperature depending on whether the RTD temperature was rising or falling prior to reaching the given temperature. The source of Hysteresis errors are difficult to quantify, though hysteresis errors of up to 0.3°C have been observed for old RTD's that have been extensively handled, while newly annealed RTD's have limited this error to 0.02°C, (reference 2).

Hysteresis errors can be minimized by taking calibration points with increasing and decreasing temperatures to beyond the measured temperature range and then averaging the results. Further, handling and manipulation of the RTD's should be minimized, which implies that high accuracy RTD's should **not** be removed from their thermowells once installed unless they are being replaced.

Process Stratification at the junction of the preheater outlet flow and the bypass flow, a warm and a cold flow stream mix (see Figure 2). Complete mixing of the flow streams will not occur within less than 2 pipe diameters of junction, and any measurement of temperature within the mixing zone will be skewed either high or low. This has been identified as a problem for the present RTD's used to measure the RIZIH temperature. And results of the cross calibration indicate that the measurement is being systematically biased 1°C to 3°C low by the preheater outlet.

Process stratification errors are best eliminated by relocating the process measuring point away from the mixing point, to ensure good mixing.

3.2.3 RTD Accuracy

During the manufacture of the RTD's material inhomogeneity and manufacturing cold work error are controllable parameters which affect the quality of the RTD accuracy. The stated tolerance for 3-wire nuclear grade RTD's purchased by Ontario Hydro for this application is:

0°C to 150°C	±0.75°C
Above 150°C	±0.5 % of temperature (@ 300°C this is ±1.5°C)

Any improvement in this accuracy will either require individual calibration and/or the purchase of new RTD's with a tighter specification.

3.2.4 Auxiliary Bay Equipment Errors

Power Supply sensitivity studies were conducted and it was found that variations in the excitation voltage caused a change of 0.0345 °C/mV. Power supply variations of ±10mV result in an error of ±0.345 °C. The power supply varied over its stated operating temperature range (21.1°C-37.8°C) by ±0.09% or ±9mV[3], which translates to an additional ±0.311°C. No estimates over a normal operating temperature range of 10°C to 40°C is available, but may be assumed to be similar.

The power supply variations and temperature errors are combined using the Root of the Sum of the Squares (RSS) method, resulting in a net power supply accuracy of ±0.464°C over the full expected operating temperature range.

Wheatstone Bridge circuits are used to convert the RTD signal to a 0-1VDC input to the DCC Computers. The nominal excitation power is 10VDC. The nominal accuracy of these bridges for an input range of -45°C to 343°C (389°C span), allowing for variations in matching resistors, is ±0.15% of span, or ±0.58°C. The bridge card operating temperature sensitivity for the range (21.1°C-37.8°C) is ±0.12% of span error, or ±0.47°C. But the true conditions in the auxiliary bay will vary between 10-40°C, and noting that the effective resistance of the bridge will vary with temperature, the bridge operating temperature sensitivity error must be extended an additional ±0.15°C. Therefore the bridge temperature sensitivity error over the operating temperature range of 10-40°C is ±0.62°C.

The nominal card accuracy and temperature variation error are combined using a RSS method, resulting in a net bridge card accuracy of ±0.849°C over the normal expected operating temperature range.

Lead Wire Resistance is assumed to be 1.2 Ohms for the non-adjustable Wheatstone Bridge card. This resistance is in addition to the RTD resistance. The actual lead wire resistance is a function of the cables used, wire gauge, length, the number of junctions and number of sharp bends made in the wire. A bridge card lead wire resistance sensitivity study was done and concluded that variations in the lead wire resistance would cause a change of -1.07 °C for every increase in of 1Ω in lead wire resistance.

A review of the Bruce A NGS cable data lists show the cables range from 27 to 61m in length in equal amounts. Hence the average length of cable is 44 m ±17m. The resistance of 16 AWG wire is 0.0134 Ω/m at 25°C, so the average lead wire resistance is 0.59 Ω ±0.23 Ω. There is a disparity of 0.61Ω ±0.23Ω between the assumed 1.2Ω lead wire resistance, and lead resistance of 0.59 Ω ±0.23 Ω. This translates to 0.65°C ± 0.246°C. This is a positive bias component which causes the indicated temperature to be higher than actual.

Self-Heating of RTD is the heat generated by bridge excitation current flow through the RTD, and is a function of I^2R, where I is the excitation current and R is the resistance, and is a function of temperature. The amount of self-heating is dependent on the RTD design. The Bruce A specification allows self-heating of up to 0.2°C at 8.5mA excitation current when installed in a thermowell in a 1 m/s fluid stream. The actual process flow past the RTD thermowell is 6-10 m/s. The present system has an excitation current of 8.1mA at 0°C and 7.4mA at 290°C. The amount of self-heating induced from this level of excitation current has not been quantified.

Reducing the excitation current to 1 mA will reduce self-heating by a factor of 54(I^2) at 290°C.

3.2.5 Computer Room

Analog to Digital Conversion of the 0-1V signal generated by the Wheatstone Bridge is performed by the Digital Control Computer (DCC) analog input subsystem. The DCC's are tested and recalibrated every major outage. The low level analog input accuracy is ±1.3 mV or ±21 counts (bits). Conversations with the Bruce A staff indicate that the inputs have 'easily' maintained this. The Input span 0 to 1V corresponds to -45°C to 343.3°C, therefore the input accuracy ±1.3mV corresponds to ±0.50°C.

Engineering Unit Conversion is the final step employed by the DCC to convert the digital input value *x* (0-1V) to an Engineering Value of temperature. The Rosemount RTD to temperature cubic equation matches the Resistance vs. Temperature[4] curves within ±0.04°C.:

3.2.6 Common Mode Errors

The cabling and grounding system design was reviewed. It appears that multiple shield grounds have been used, which can lead to ground loops. Conversations with station staff indicate that this has not been a problem.

Shielded cabling is used for the signal run from the RTD to the DCC. Both the Wheatstone Bridge cards and the DCC Analog input cards are located in large metal cabinets which are themselves grounded. Both practices should reduce the effect of RFI and EMI. Conversations with station staff indicate that this has not been a problem.

3.2.7 Summary of Measurement Loop Errors

The individual measurement loop errors are combined using the Root of Sum of Squares (RSS) technique to determine the total loop error.

The following is a complete listing of the RTD temperature measurement loop error components, separated as long term and short term:

Table 1 Summary of Loop Errors

Area	Error Description	Total Error	Long Term Variable	Fixed-Short Term Variable
Reactor	Gamma Ray Heating	negligible		
	Transmutation	Not Apparent		
	Radiation Induced Currents	Not Apparent		
	Insulation Dielectric	Not Apparent		
	Aging / Drift	±0.2°C	±0.2°C	
	Aging / Drift radiation	-.027±0.024°C		-.027±0.024°C

Install	Stem Losses	<<-0.01°C		<<-0.01°C
	Thermoelectric Errors	Not Apparent		
	RTD-Thermowell contact	Not Apparent		
	Handling Errors - Hysteresis	±0.02°C	±0.02°C	
	Process Stratification, not included in total.	Quadrant Specific, -1°C to -3°C		
RTD	Interchangeable RTD Accuracy	±1.5°C		±1.5°C
Aux. Bay	Power Supply	±0.464°C	±0.311°	±0.345°C
	Wheatstone Bridge	±0.849°C	±0.62°C	±0.58°C
	Lead Wire Resistance	+0.65±0.246°C		+0.65±0.246°C
	Self Heating	+0.2°C		+0.2°C
DCC	Analog Input	±0.5°C	±0.166°C	±0.471°C
	Engineering Unit Conversion	±0.04°C		±0.04°C
	Root Sum Square - RSS	+0.823±1.881°C		
	Long Term Drift (2σRIH-d)		±0.741°C	
	Fix and Short-term Variations			+0.823±1.729°C

The Auxiliary Bay Power Supply and Wheatstone Bridge errors were divided as both short-term and long-term. The errors caused by operating temperature variations is considered long-term, while the remainder of the errors were considered fixed or short-term. The DCC Analog Input error was divided as both short-term and long-term. A one-third, long-term drift component is used consistent with previous analysis of loop error.

4. LOOP CROSS-CALIBRATION

The preceding section details the errors and their possible magnitude by review of available interchangeable component tolerance data. The resultant total error would therefore represent a worst case error. Loop Cross-Calibration provides a method of more realistically quantifying the actual loop error, by comparing the RIH RTD measurement to an accurate reference. The FINCH inlet side channel differential temperature RTD's can provide between 5 and 6 measurements of the inlet header temperature per quadrant. The average of these measurements is then used as an accurate reference.

As a sub-program to the Power Raise program, an evaluation was performed by Bruce A Reactor Safety which established a non-intrusive means of cross calibrating the mixing zone inlet header RTD's on-load, using the FINCH mounted RTD's as a reference. This evaluation provides the basis for the cross-calibration technique. The cross-calibration method was extended to also evaluate the uncertainty associated with inner zone temperature measurement for RTD's installed directly in the header itself.

4.1 Loop Cross-Calibration Setup

The Loop Cross-Calibration uses a data logger to record and time stamp the quadrant specific inlet header temperature via 5 or 6 FINCH RTD's, while the DCC computer and plant status monitoring system computer are used to record and time stamp the RIH temperature. The FINCH data points are then averaged and time-paired (matched) with the RIH temperature. The instantaneous difference between the FINCH average and the RIH temperature is averaged and the standard deviation (s_i) of the difference is calculated. The average represents the systematic bias (d_i) while the standard deviation (s_i) is used to determine the random uncertainty in the measurement .

For the period of the Cross-Calibration, one of the RTD's on the inlet side from each of the FINCH differential temperature measurements is used to measure the actual Reactor Inlet temperature. Within each quadrant these FINCH RTD's are used to create the reference temperature for calibration of the actual RIH RTD.

The Central Limit Theorem from statistical analysis states that the accuracy of the reference will be:

$$\frac{2\sigma_{FINCH}}{\sqrt{n_i}}$$

Where: $2\sigma_{FINCH}$ = FINCH RTD accuracy
n_i = the number of reference FINCH RTD's used within the i^{th} quadrant.

From this it can be seen that the accuracy improves with the number of FINCH RTD's used.

4.2 RTD's Located in Mixing Zone

The first phase of this program quantified the measurement uncertainty associated with the original design location, the R and S paired RTD's, (see Figure 2). The original design placed dual RTD's less than 2 pipe diameters down stream from the confluence (junction) of the pre-heater and by-pass flows. An error consisting of a systematic offset (bias) and a random component was quantified and the i^{th} quadrant measurement uncertainty (D_i) for an RTD located in the mixing zone is given as:

$$D_i^+ = d_i + 2\sqrt{s_i^2 + (0.1D_i^+)^2 + \left(\frac{\sigma_{FINCH}}{\sqrt{n_i}}\right)^2 + \left(\frac{\sigma_{RIH-d}}{\sqrt{2}}\right)^2}$$

Where d_i = the observed cross-calibration bias component
s_i = the observed cross-calibration random component
$2\sigma_{FINCH}$ = FINCH RTD accuracy
$2\sigma_{RTH\text{-}d}$ = RTD measurement loop drift component
n_i = the number of reference FINCH RTD's used within the i^{th} quadrant

Note, a positive uncertainty indicates that that the temperature measurement is below the actual temperature.

The $0.1D_i^+$ represents the non-observed mixing variations attributed to seasonal variations of the pre-heater.

The above equation may also be expressed as

$$Error_{max+} = (Bias + Random)_{Calibration/Mixing} + Reference\ Accuracy + RTD\ Drift$$

To date this method has been used for Bruce A unit 3 at 84% reactor power. The bias (d_i), random error standard deviation (s_i) and calculated uncertainty (D_i^+) are shown in Table 2.

Table 2 Unit 3 Mixing Zone RTD Cross Calibration Results

	NE	SE	SW	NW
bias (d_i)	2.682	1.963	2.258	1.928
random (s_i)	0.282	0.339	0.345	0.323
Uncertainty (D_i^+)	3.934	3.218	3.555	3.128

4.3 RTD's Located in Actual Inlet Header

Spare thermowells exist near the ends and center of each of the four inlet headers. The thermowells at the ends of the header are at least 5 pipe diameters away from the confluence of the pre-heater and by-pass flows. These thermowells provide suitable and viable alternate locations that can be used to minimize the measurement uncertainty. The centrally located RTD's are too close to the flow 'dead zone' between the north south header flows to accurately be cross-calibrated.

The uncertainty equation can be simplified for the RTD measurements located in the header itself. The $0.1D_i$ component represented the long term randomness in the mixing zone caused by Preheater load variations. But, since these RTD's are more than 2 header diameters from the mixing area the $0.1D_i$ is not applicable.

Cross-calibration is used to determine both the systematic bias and short term random components of the instrument error observable during the cross-calibration period. Long-term variations of the instrument error are accounted for by the RTD drift term ($2\sigma_{RIH-d}$).

The reference accuracy remains the $2\sigma_{FINCH}/\sqrt{n_i}$ term. Where n_i is the number of FINCH RTD's used within the i^{th} quadrant for the cross-calibration. And, $2\sigma_{FINCH}$ was previously evaluated to be ±1.46°C.

The measurement uncertainty equation for a single element RTD located in the Reactor Inlet Header will be:

$$D_i^+ = d_i + \sqrt{(2s_i)^2 + \left(\frac{2\sigma_{FINCH}}{\sqrt{n_i}}\right)^2 + (2\sigma_{RIH-d})^2}$$

Note, the $2\sigma_{RIH-d}$ is not divided by $\sqrt{2}$, as only one RTD signal is used in each quadrant, as opposed to the average of the R, S RTD signal.

To date this method has been used for Bruce A unit 3 at 84% reactor power. The bias (d_i), random error standard deviation (s_i) and calculated uncertainty (D_i^+) are shown in Table 3.

Table 3 Unit 3 Relocated RTD Cross Calibration Results

	NE	SE	SW	NW
bias (d_i)	-0.001	-0.0001	0.117	N/A
random (s_i)	0.48	0.4	0.39	N/A
Uncertainty (D_i^+)	1.56	1.55	1.66	N/A

As expected the relocated RTD's have little bias indicating that mixing of the preheater outlet and preheater bypass flow streams is complete.

4.4 Limitation of Cross Calibration

This method of cross calibrating the RIH RTD's provides a method of reducing the measurement uncertainty. Its application however, is limited by the following factors:

- the calibration is expensive and time consuming to perform and must be performed for each RTD,
- the calibration is of the instrumentation loop; and if any component changes the calibration will need to be repeated,
- the calibration is limited by accuracy of the reference RTD's,
- it requires modification of DCC code to adjust alarm limits based on quadrant specific measurement uncertainty and
- in the case of the mixing zone RTD's, the error is also load dependent.

5. ALTERNATIVE DESIGNS

In the previous sections we have discussed the existing Reactor Inlet Header design, and how and where the RIH temperature is measured. We also determined the RIH temperature loop accuracy in detail. By using a cross calibration technique we measured the quadrant specific measurement uncertainty. It is apparent that cross calibration can be used to reduce the measurement uncertainty. It was also useful in quantifying the magnitude of process stratification induced error occurring in the present Inner Zone RIH temperature measurement location. Unfortunately, the limitations associated with cross calibration do not make it the most desirable long-term solution to improving RIH temperature measurement.

Any long-term efforts to reduce the RIH temperature uncertainty must:

- eliminate the effects of the process stratification associated with the mixing zone,
- provide redundancy, as this measurement has become a critical parameter,
- provide component interchangability,
- be easily installed and maintainable and
- have minimal impact upon the DCC's.

The optimal solution for reducing the measurement uncertainty is to eliminate the largest errors and make use of different transmitter manufactures on each leg of the dual element RTD to provide diversity of equipment and lower the software quality assurance requirements. The best overall solution included the following:

- Relocate the Inner Zone RIH temperature measurement away from the mixing zone and into spare thermowells in the header itself, to eliminate the process stratification effects.
- Use new, calibrated 4-wire dual element RTD's in place of OH standard interchangeable RTD's .
- Use high quality commercially available smart temperature transmitters to convert the RTD signal rather than the Wheatstone Bridge cards. The transmitters must be complete with a zero and span adjustment and leadwire compensation.

It is expected that the above solution will provide a measurement loop accuracy of ±0.72°C.

6. CONCLUSIONS

The Reactor Inner Zone Inlet Header (RIZIH) temperature measurement is a critical parameter for both the safe and economic operation of the Bruce A NGS units. The RIZIH temperature has been increasing over time and is one of several parameters preventing the units returning to 94% power.

At present, a large RIZIH temperature measurement uncertainty margin is provided between the true RIZIH limit and the applied limit. A reduction of this uncertainty would allow the units to operate closer to the true limit, with no reduction in safety.

The RIZIH temperature uncertainty was determined by a detailed analysis and cross-calibration. By detailed analysis the uncertainty was determined to be +0.823±1.88°C, not including a process flow stratification error of 1-3°C which is both quadrant and zone specific. Cross-calibration measured the quadrant specific error and determined that the uncertainties ranged from 3.22°C to 3.93°C at 84% reactor power, including the process flow stratification error. Limitations of the cross-calibration method will be expensive to maintain in the long term.

A more acceptable solution to reduce the RIH measurement uncertainty is a proposal based on commercially available smart transmitter technology, and the use of dual element 4-wire RTD's installed in spare thermowells located in the RIH and away from any incomplete mixing zones. This solution would reduce the measurement uncertainty to ±0.72°C, and not be constrained by the limitations of cross-calibration.

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