# MANAGING SYSTEMATIC ERRORS IN THE NBSR THERMAL POWER CALORIMETRIC MEASUREMENTS

**Dağıstan Şahin, Samuel J. MacDavid**
National Institute of Standards and Technology Center for Neutron Research
100 Bureau Dr., Gaithersburg, MD 20899 USA
dagistan.sahin@nist.gov; samuel.macdavid@nist.gov

## ABSTRACT

There has been a calorimetric misbalance between the primary and secondary loops of the National Bureau of Standards Reactor (NBSR) since the installation of a set of new heat exchangers in the early 90's. The NBSR's primary and secondary process instrumentation were investigated to resolve the underlying causes. The main issue was found to be the immersion length of the thermowells, resulting in non-exemplary process measurements. Furthermore, thermal insulation on various temperature sensors was found to be degraded. Hence, the following were found to be inconsistent: the heat exchanger output temperatures, previously-used differential temperature sensors, reactor inlet sensor, and the reactor outlet temperature indications. Therefore, thermodynamic analyses using these sensor measurements were inconclusive. Secondly, the discrepancy between primary and secondary loops and the gradual inconsistency between primary side sensors went largely unnoticed. We implemented sustainable, state-of-the-art upgrades to resolve systematic errors in the NBSR reactor thermal process instrumentation. Several digital upgrades were completed, along with detailed 50.59 reviews. Redundancy, defense-in-depth, reliability, diversity and accuracy of the thermal monitoring system was established by implementing an inclusive engineering approach by analyzing the sensors as a whole system instead of individual assessments. The upgrades produced two important outcomes. First, the long-term existing calorimetric discrepancy between the primary and secondary loops was resolved. Secondly, excellent agreement was achieved within the primary process measurement instrumentation, resulting in reliable and stable thermal power assessment. We will present lessons learned performing instrumentation upgrades and our future enhancement plans in process monitoring for the NBSR reactor.

*Key Words*: RTD, thermowell, thermocouple, flow sensor, temperature sensor

## 1 INTRODUCTION

We implemented sustainable, state-of-the-art upgrades to resolve systematic errors in the NBSR reactor thermal process instrumentation. The upgrades revealed two significant outcomes. First, a long-term existing calorimetric inconsistency between the primary and secondary loops was resolved. Secondly, excellent agreement was achieved within the primary process measurement instrumentation, resulting in reliable and stable thermal power assessment. Additionally, routine reactor parameter checks and calibration procedures were changed to allow early recognition and detection of possible problems. This report documents the deficiencies, corrections, and improvements in thermal power measurement instrumentation and calibration procedures. Details of these changes were documented in several Engineering Change Notices (ECN), five of which required 50.59 evaluations.

## 1.1 Inconsistency Between Primary and Secondary Calorimetric

There has been a calorimetric misbalance between the primary and secondary loops of the NBSR reactor since the installation of a set of new heat exchangers in 1994. The determined cause of incorrect readings was the improper immersion depth of the secondary side thermowells leaving a portion of the sensitive sensor area outside the bulk flow as shown in Fig. 1. The incorrect installation was exacerbated by the use of low quality thermocouples without proper junction bonding. The immersion was 1 inch in the 12-inch pipe and the tip of the thermowell merely made contact with the bulk process fluid. As a general rule, the tip of the temperature sensor should be located between 2/3 R to R (where R is pipe radius), or at least an inch plus the active sensor length, to obtain representative temperature measurements. Consequently, the secondary calorimetric was showing a reactor thermal power of about 29 MW when the primary loop calorimetric measurements were about 20 MW. New thermowell assemblies with proper immersion were installed and the calorimetric imbalance was corrected. Secondary loop calorimetric currently measures 20 MW ± 3 MW. Schematics of the previous and current thermocouples installed in the secondary loop are presented in Fig. 1.

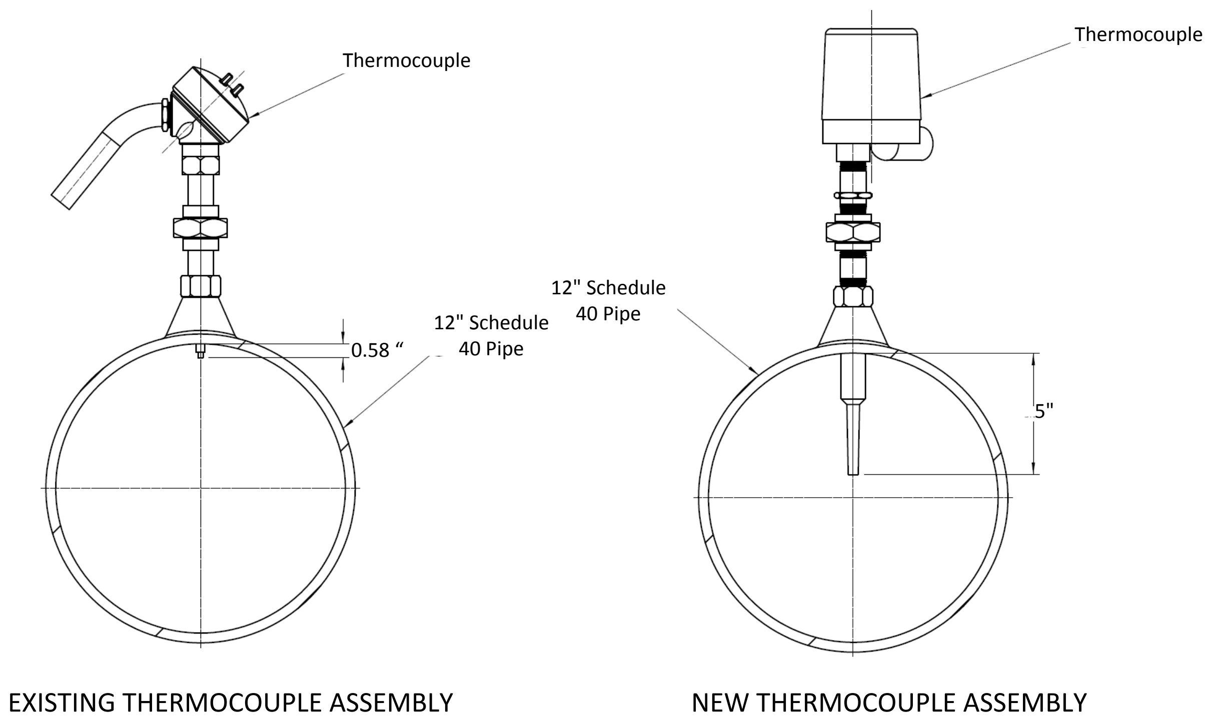


**Figure 1. Thermocouple installation, previous and new thermowell assemblies**

## 1.2 Systematic Errors in the Primary Loop Instrumentation

The NBSR reactor thermal power output is measured by a digital recorder unit called the BTUR. The unit uses two RTDs to measure the primary loop temperature differential and a Venturi flow meter for primary flow. The BTUR unit combines these measurements to assess the reactor thermal power output. A lower than expected operating power was discovered due to a gradual increase in reactivity as measured by shim rod heights at the end of cycles. This increase in reactivity could not be accounted for using the BTUR data. A variety of sensors at different locations in the primary piping were compared in an attempt to narrow down the faulty component. However, the heat exchanger output temperatures, previously used differential temperature sensors, reactor inlet sensor and the reactor outlet temperature indications were found to be inconsistent as shown in Fig. 2 (August 2015). Therefore, thermodynamic analyses using these sensors were inconclusive. An inspection of sensors and thermal bath calibration checks was performed on the primary process temperature sensors. Measured temperature deviations by means of a calibrated thermal bath revealed which RTD sensors had drifted. Hence, the BTUR was reading higher than the actual differential temperature; therefore, the reactor was operating less than 20 MW, lower than licensed power. Additionally, the immersion length for some of the RTD sensor thermowells was less than ideal.

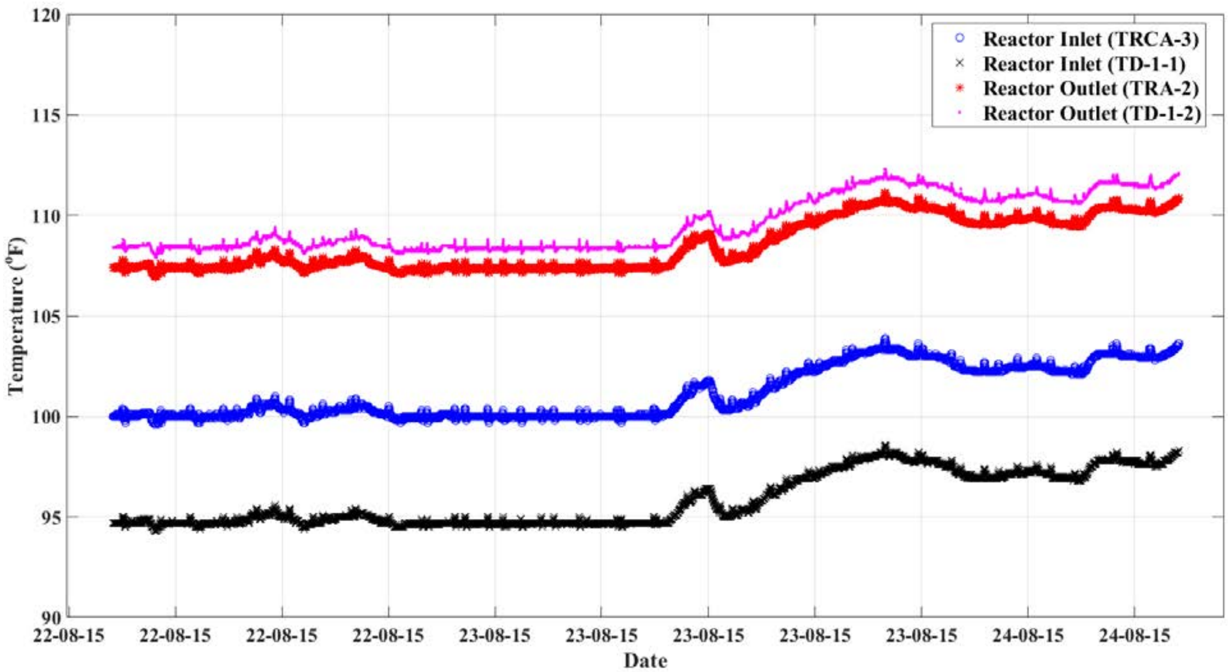


**Figure 2. Primary Loop Inlet and Outlet Temperature Readings During August 2015**

## 2 IMPLEMENTATION OF CHANGES

The cause of the undiscovered sensor drifts was found to be the existing calibration procedures, which did not require a traceable physical source, such as a thermal bath, to verify sensor accuracy. Additionally, this long-term drift went largely unnoticed with BTUR individual temperature data not being displayed for direct comparison to other data points. The drifted RTDs were replaced, the calibration procedures were updated, and adequate data display modifications were implemented. The entire instrumentation loop from the RTD in a thermal bath up to the BTUR calculation and display were verified to be correct within equipment and sensor tolerances. Thermowells were replaced for optimum immersion lengths dependent on the piping size. Additional features were added to the sensors, such as spring loaded mechanisms to ensure proper contact and stepped thermowells improving response times.

A schematic diagram showing the instrumentation before August 2016 is presented in Fig. 3. Fig. 4 shows the final configuration, including the latest changes that were implemented. The current configuration, consisting of digital and analog transmitters for temperature and flow, satisfies defense-in-depth, redundancy, reliability, diversity and accuracy for process measurements. Primary loop temperature and flow are being monitored by multiple sensors. Reactor primary coolant temperatures are measured by RTD and thermocouples providing defense-in-depth. The average probability of failure on demand ($PFD_{AVG}$) for the new digital transmitters (Rosemount® 644), considering undetected failures of hardware, is 1.3x10$^{-4}$ probability of failure per hour (PFH). Compared to $PFD_{AVG}$ of 2.6x10$^{-3}$ PFH for the previous Acromag® transmitter (assuming same partial test interval of 1 year). The total system (RTD in a high-stress environment and transmitter) $PFD_{AVG}$ using Rosemount® 644 is 4.8x10$^{-4}$ PFH. Refer to Appendix A for detailed analysis of failure rates. The primary temperature instrumentation uses a combination of different brand digital (Rosemount® 644, and Acromag® 250R-JL00) and analog (Acromag® 250T-RBP1) transmitters. Primary coolant flow is measured by two different transmitters, a nuclear grade (Weed instruments) and an analog tramsmitter (L&N Model 470). The diversity of the transmitters prevents a common cause failure mode from causing a complete loss of all process indications due to a single failure.

Rosemount® 644 transmitters used for BTUR inlet, BTUR outlet, and TRCA-3 employ Callendar-van Dusen RTD sensor matching. The expected total measurement uncertainty of these sensor-transmitter systems is about 0.2 F. The transmitter and circuitry for the BTUR flow meter (FR-1) were replaced, and stability was improved. The relative standard deviation in the FR-1 reading was reduced to 0.7 %.

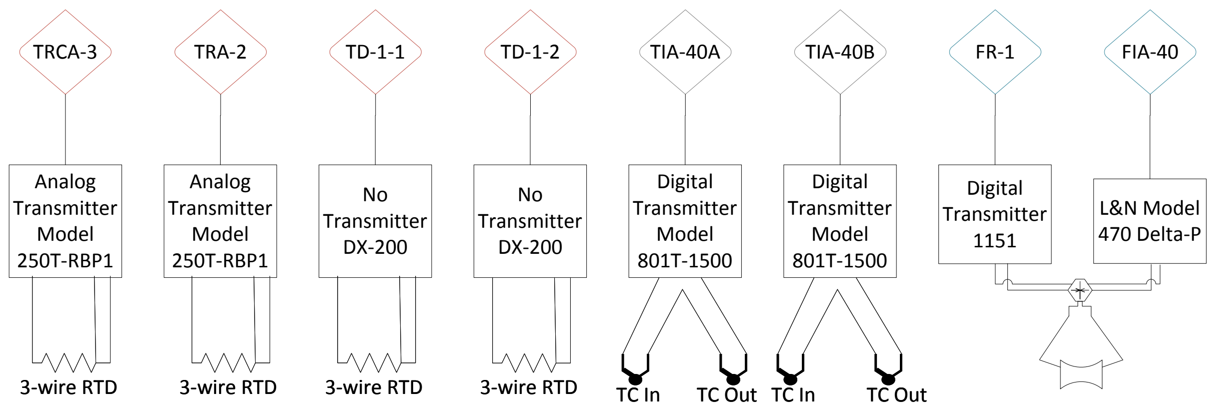


**Figure 3. Primary process instrumentation previous configuration**

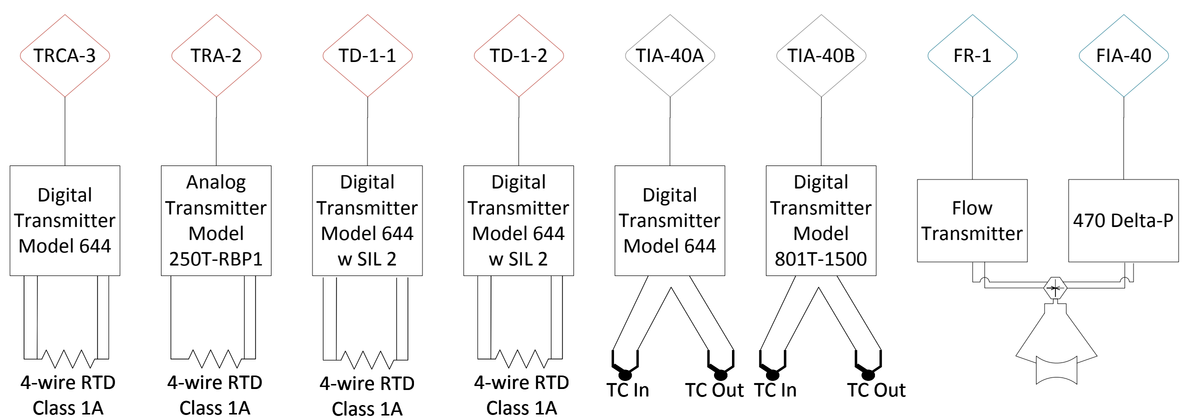


**Figure 4. Primary process instrumentation configuration after upgrades**

Recent temperature readings in August 2016 are shown in Fig. 5. Compared to the previous trends as seen in Fig. 2, the stability and the accuracy of readings are greatly enhanced. Table 1 shows recent readings for the primary instrumentation.

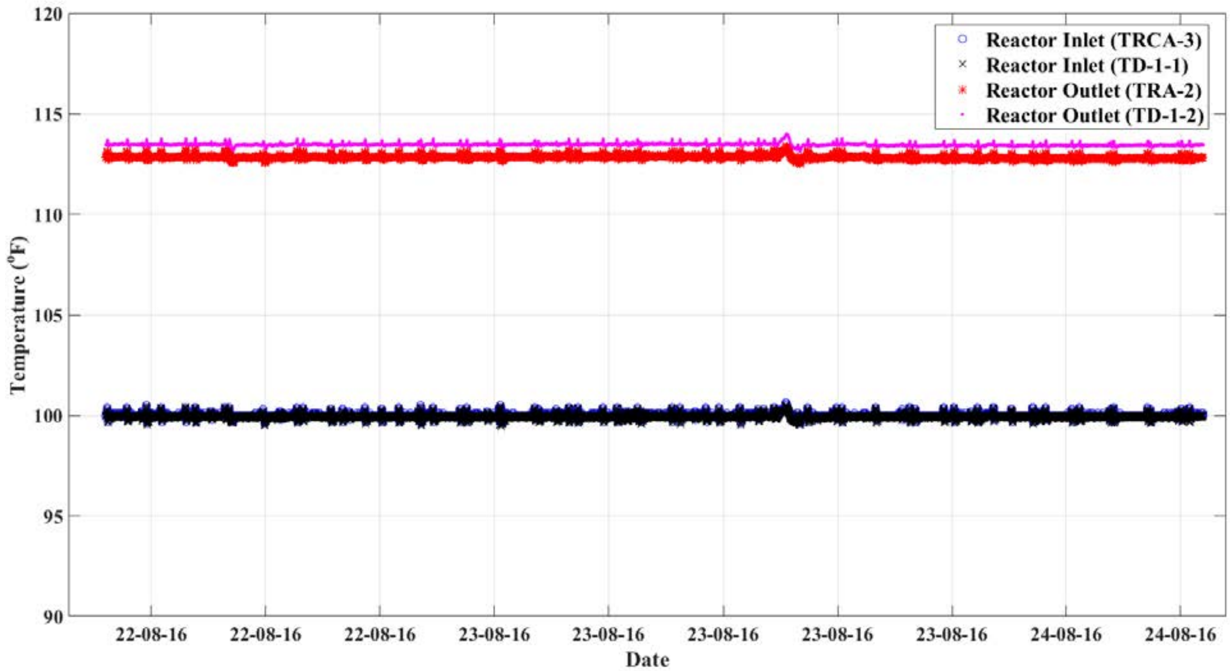


**Figure 5. Primary Loop Inlet and Outlet Temperature Readings after upgrades**

## 3 CONCLUSIONS

We implemented sustainable, state-of-the-art upgrades and resolved systematic errors in the NBSR reactor thermal process instrumentation. The new instrumentation provides redundant, diverse, reliable and highly accurate measurements of primary and secondary process conditions. We resolved the calorimetric inconsistency between primary and secondary loops and systematic errors in the primary process measurements.

The main cause of the drifting in process instrumentation was found to be the improper calibration procedures, which did not require a traceable physical source. Hence, the existing calibration procedures were updated to contain traceable physical sources ensuring proper indication from sensor to indicator through the full operating loop. Physical source check frequencies were implemented to ensure future drifting to be recognized and corrected in a timely manner. Control room display parameters were changed to allow direct comparison of similar parameters by the reactor operators. Hourly reactor operator log sheets were updated to allow direct comparison of important parameters.

Ongoing work is focused on improving accuracy in inlet flow measurement sensors, FRC-3 and FRC-4, and heat exchanger flow measurement sensors, FR-20 and FR-21. Installation of a triple redundant RTD sensor system for the reactor outlet measurement is planned to increase accuracy and online sensor cross check procedures. Additionally, the temperature sensors in the primary heat exchanger outlets is going to be replaced. As shown in Fig. 5, there are relatively small thermal power transients which are caused by the strainer system. When in operation, the strainer pumps lower the secondary flow for ten minutes approximately every two hours. A VFD based flow controller is to be installed to stabilize secondary flow. A continuing control room upgrade project by the same team involved here benefits from the knowledge of a system wide analysis in upgrading and displaying information.

# 4 ACKNOWLEDGMENTS

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# 5 DISCLAIMER

Certain commercial equipment, instruments, or materials are identified in this study to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

# 6 REFERENCES

1. Exida, "IEC 61508 Functional Safety Assessment, 644 4-20mA / HART Temperature Transmitter", ROS 12/04-020 R002, September 5, 2012
2. Exida, "Failure Modes, Effects and Diagnostic Analysis", ROS 03/05-11 R001, June 14, 2015

## APPENDIX A - Comparison of Analog vs. Digital Transmitters Failure Modes/Rates

The existing analog transmitters were Acromag® 250 series, two-wire transmitters. The transmitter condition DC voltage to a 4 to 20 mA process current output. The Demonstrated Mean Time Between Failure (DMTBF) for the 250 series is 195 years. The input circuit is isolated. Acromag® 250 is an analog transmitter externally loop-powered by a 24VDC power supply. The output and the DC power share the same pair of twisted copper wires. The transmitter acts as a variable resistor in series with the load and the DC supply provides an output current proportional to the sensor input. When the sensor input fails, sensor connection is lost, or an electronics failure happens the transmitter fails to low output. This results in a very low reactor outlet temperature reading. Once a failure is recognized by reactor operators, the reactor would be secured and appropriate corrective actions would take place.

The installed transmitters are Rosemount® 644HANAQT smart transmitters with a safety certificate IEC 61508 (SIL 2) of Failure Mode Effects and Diagnostic Analysis (FMEDA) data (Highway Addressable Remote Transducer (HART) only). The transmitter, also loop-powered by a 24VDC power supply externally, provides the equivalent functionalities as the Acromag® transmitter and has additional capabilities. The proposed transmitter provides higher accuracy for sensor reading. The transmitter provides additional functionality by means of a microprocessor. An independent backup alarm circuit is connected to the digital to analog (D/A) converter at the output of the transmitter. In the event of a sensor input failure, sensor connectivity loss, or a firmware failure the fail signal enables the backup circuit. The backup circuit does not possess any firmware for executing the action. The backup circuit sets the output of the transmitter to high or low based on an analog switch on the transmitter. The new transmitter is to be configured to fail high. The existing and proposed transmitter actions for probable events in Table I show the adequacy of the replacement. In the possible event of a malfunctioning microprocessor, 99% of the software failures, the transmitter will output high causing rundown and annunciators to alert the operators.

However, it is possible that the malfunction of the transmitter may stall the microchip resulting in a constant reactor outlet temperature reading and prevent it from actuating in the event of aforementioned accident scenarios. The 644HANAQT is certified to IEC 61508 for single transmitter use and has a hardware fault tolerance of 0. The Mean Time Between Failure (MTBF) for the 644HANAQT is specified as 50 years. The transmitter is certified to SIL2, and would fail safe in about 90 to 99 % of all failures. The software/firmware on the 644HANAQT microchip is certified to SIL3 level, with a greater than 99% fail safe probability. The condition when the software failed in a different way than previous transmitter (i.e.

stalled) is 1% of the failure probability. So, 99% of the failures of the new transmitter would either fail safe or fail in the same way with the existing transmitter, i.e. no output.

The average probability of failure on demand ($PFD_{AVG}$) for 644HANAQT considering undetected failures of hardware is $1.3x10^{-4}$ failure per hour (PFH), expected once in system lifetime. Compared to $PFD_{AVG}$ of $2.6x10^{-3}$ PFH for the existing Acromag® transmitter (assuming same partial test interval of 1 year). The total system (RTD in a high-stress environment and transmitter) $PFD_{AVG}$ using 644HANAQT is $4.8x10^{-4}$ PFH.

The new sensor and transmitters were proof tested/calibrated based on manufacturer requirements annually. This type of proof test covers 96% of transmitter dangerous undetected (DU) and 99% of temperature sensor DU failures. The transmitter and RTD sensor would be replaced after ten years of operation. Therefore, the probability of a sensor system malfunction in a different way than existing will be kept minimal and accident analyses in the updated FSAR would not be affected.

The following analysis is based on the FMEDA and certification reports for Rosemount® 644 4-20mA HART Temperature Transmitter [1,2].

The failure modes for the 644 HART transmitter are; Fail-Safe State, Fail Safe, Fail Dangerous, Fail Dangerous Undetected, Fail Dangerous Detected, Fail High, Fail Low, Fail No Effect, and Annunciation Undetected. Fail No Effect and Annunciation Undetected are assumed as unsafe undetected failures since they will not cause the transmitter to result in a safe state. Fail High and Fail Low categories are classified as safe. Hence, Fail High initiates the safety feature, and Fail Low is same as previous, where operator intervention is required. Failure rates for evaluated conditions are listed in Table II.

**Table I: Event scenarios for the existing and proposed transmitter**

| Event | Acromag® 250 | Rosemount® 644HANAQT |
|---|---|---|
| Power Loss | Fail low | Fail low |
| Sensor input failure or connection | Fail low | Fail high |
| Power supply trouble | Fail low | Fail high |
| Firmware Failure | N/A | Fail high |
| Microchip Stalled | N/A | Read-Constant |
| PFD | $2.6x10^{-3}$ | $1.3x10^{-4}$ |

**Table II: Failure Rates 644 RTD Configuration (FIT= 1 failure per $10^{-9}$ hours) [1, Table 4]**

| Failure Category | Failure Rate (FIT) |
|---|---|
| Fail High (detected by logic solver) | 26 |
| Fail Low (detected by logic solver) | 290 |
| Fail detected (int diag) | 267 |
| Fail low (inherently) | 23 |
| Fail Dangerous Undetected | 70 |
| No Effect | 105 |
| Annunciation Undetected | 9 |

The Safe Failure Fraction (SSF) is given by;

$$SSF = 1 - \frac{\lambda^{DU}}{\lambda^{total}} \quad (1)$$

Where $\lambda_{du}$ is the undetected unsafe failure rate and $\lambda_{total}$ is the total failure rate.The failure rate for an RTD high-stress environment is 8000 FIT [1, Table 6]. Using the typical failure mode distributions for RTDs [1, Table 8], following rates are calculated.

$$\lambda^{L} = (8000) * (0.7 + 0.29) = 7920\ FITs \quad (2)$$

$$\lambda^{DU} = (8000) * (0.01) = 80\ FITs \quad (3)$$

The failure rate contribution of the 644 HART Temperature Transmitter when used with a 4-wire RTD is

$$\lambda^{SD} = 31\ FITs \quad (4)$$

$$\lambda^{DD} = 286\ FITs \quad (5)$$

$$\lambda^{DU} = 30\ FITs \quad (6)$$

When these failure rates are added, the total for the temperature sensor subsystem is

$$\lambda^{total} = 7920 + 80 + 31 + 286 + 30 = 8347\ FITs \quad (7)$$

$$\lambda^{DU} = 80 + 30 = 110\ FITs \quad (8)$$

$$SSF = 1 - \frac{\lambda^{DU}}{\lambda^{total}} \quad (9)$$

$$SSF = 1 - \frac{110}{8347} = 0.99 \quad (10)$$

Where SSF is the safe failure fraction. The SFF for this temperature subsystem is 99 %. Assuming that the logic solver can detect both over-range and under-range, low and high failure can be classified as a safe detected failure for this application;

$$\lambda^{SD} = \lambda^{L} + \lambda^{H} = 8236\ FITs \text{ (safe detected failure rate)} \quad (11)$$

$$\lambda^{DU} = 110\ FITs \text{ (dangerous undetected failure rate)} \quad (12)$$

$\lambda^{DD} = 0$ (detected dangerous is included in safe detected, hence the fail high brings the system to a safer state.) (13)

The Probability of Failure on Demand (PFD) for a 1oo1 system is given by;

$$PFD_G = (\lambda^{DU} + \lambda^{DD}) x\ t_{CE} \quad (14)$$

$$PFD_G = (\lambda^{D}) x\ t_{CE} \quad (15)$$

$$PFD_G = \lambda^{DU} x (\frac{T_1}{2} + MTTR)) + \lambda^{DD} x\ MTTR \quad (16)$$

With,

$$t_{CE} = \frac{\lambda^{DU}}{\lambda^{D}} x\ (\frac{T_1}{2} + MTTR) + \frac{\lambda^{DD}}{\lambda^{D}} x\ MTTR \quad (17)$$

$$\lambda^{D} = 8347\ FITs \text{ (total failure rate)} \quad (18)$$

Assuming Mean Time to Restoration (MTTR) = 8 hours, and proof test interval ($T_1$) of 1 years, the probability of failure on demand due to an undetected failure for the RTD-transmitter system is;

$$PFD_{avg} = \lambda^{DU} x (\frac{T_1}{2} + MTTR) \quad (19)$$

$$PFD_{avg} = (110) x \left( (365 * \frac{24}{2}) + 8 \right) = 4.8 \text{ x } 10^{-4} \text{ PFH} \quad (20)$$

The probability of failure on demand considering ***only*** the transmitter (due to an undetected failure) is;

$$PFD_{avg} = (30) x \left( 365 * \frac{24}{2} + 8 \right) = 1.3 \text{ x } 10^{-4}\ PFH \quad (21)$$

For the Acromag® 250T, since there is no diagnostics or fail-safe functionality, we assume all failures result in the same outcome, i.e. low output;

The DMTBF is 195 years,

$$\lambda^D = \frac{1}{195*24*365} = 585.4\ FITs \tag{22}$$

$$PFD_{avg} = 585.4 * \left(365 * \frac{24}{2} + 8\right) = 2.6 \text{ x } 10^{-3} PFH \tag{23}$$