On-line Monitoring and Calibration Techniques in Nuclear Power Plants

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Abstract. Years of research, testing and experience in the field of sensor diagnostics have yielded many technologies which offer financial as well as operational benefits to the nuclear industry. Among these technologies are On-Line Monitoring (OLM) and On-Line Calibration of critical process monitoring sensors such as resistance temperature detectors (RTD), thermocouples, and pressure transmitters to name a few. The remote access and verification of these sensors have been shown to limit the exposure of maintenance personnel to harsh environments while at the same time effectively and efficiently diagnosing the health and performance of these sensors. In addition to sensors, technologies exist in determining not only the health of instrumentation and control (I&C) cabling that carries the signals from these sensors, but also these same cable testing techniques can be used in the remote evaluation of many end devices used in safety related operations as well.

Given these advances in sensor system monitoring techniques it would seem to follow that nuclear utilities from around the world would be applying these tried and true techniques to optimize up time and to provide additional confidence in the output of processing sensors. However, although several of the world's regulatory bodies have approved of the concept of these techniques, few utilities have undertaken to fully embrace on-line monitoring and on-line calibration of nuclear process sensors.

In the United States efforts are now underway, with representatives of the U.S. nuclear industry and nuclear power plant vendors to obtain generic NRC licensing for the use of OLM in nuclear power plants. If approved, generic licensing will help pave the way toward greater implementation of OLM and its related calibration techniques.

Keywords: nuclear power plants, noise analysis, instrumentation and control, next generation reactors, sensor response time testing, sensing line blockages, calibration monitoring.

Abbreviations/Acronyms

ANL	Argonne National Laboratory
APSD	Auto Power Spectral Density
I&C	Instrumentation and Control
LCSR	Loop Current Step Response
NASA	National Aeronautics and Space Administration
NRC	U.S. Nuclear Regulatory Commission
OLM	On-Line Monitoring
RTD	Resistance Temperature Detector
SER	Safety Evaluation Report
TDR	Time Domain Reflectometry

1. INTRODUCTION

Along with the increasing demands for low cost environmentally friendly energy has come the renewed interest in developing advanced nuclear reactors and instrumentation and control (I&C) technology for next generation nuclear power plants. In the midst of this effort we should not lose sight of the opportunities that are available in fully utilizing the resources and information available in the sensing applications that are currently in use and that will remain the backbone of operational information flow for new reactor designs. As shown in Figure 1, temperature detectors, pressure transmitters and the cabling that connects them with the digital world will remain virtually the same. However, new technologies, such as on-line monitoring and calibration have yet to be fully exploited and thereby remain an opportunity for existing as well as new reactor sophistication.

2. TEMPERATURE SENSORS AND CABLE DIAGNOSTICS

It is well known that the response time of RTDs and thermocouples is subject to change over time.

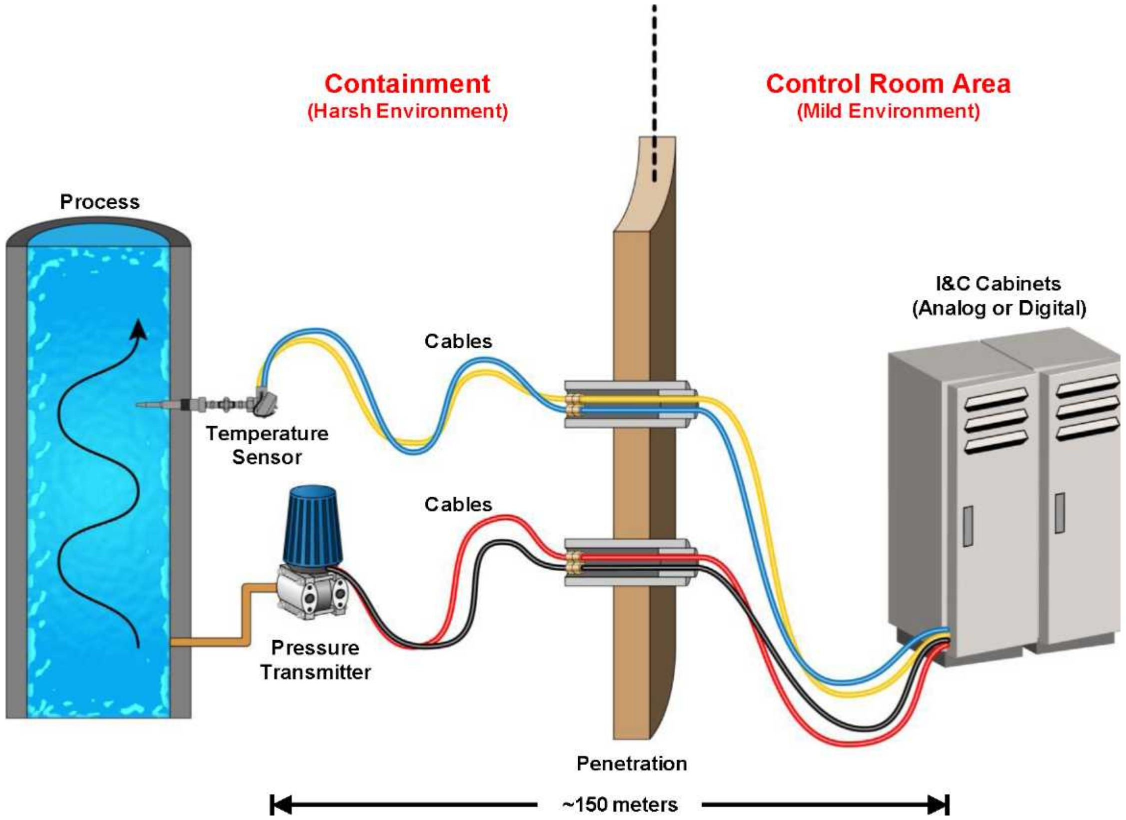

Fig. 1. Illustration of Process Sensing System and Connections in a Nuclear Power Plant

Many factors contribute to this degradation, for example, vibration can cause RTDs and thermocouples to move out of their thermowell and result in an increase in response time. Even a very small movement can cause a large change in response time. Temperature variations can also result in changes in sensor response time. For example, inherent voids in sensor insulation materials can expand or contract and cause the response time to change. For these and other reasons, response time of RTDs and thermocouples is measured periodically in nuclear power plants (See Figure 2). The measurement is made using the Loop Current Step Response (LCSR) method and the noise analysis technique as described in [1].

Also, the performance of sensors such as thermocouples, thin-film RTDs, strain gages, and other resistive devices that are used in nuclear power plants for measurement of surface conditions of pipes,

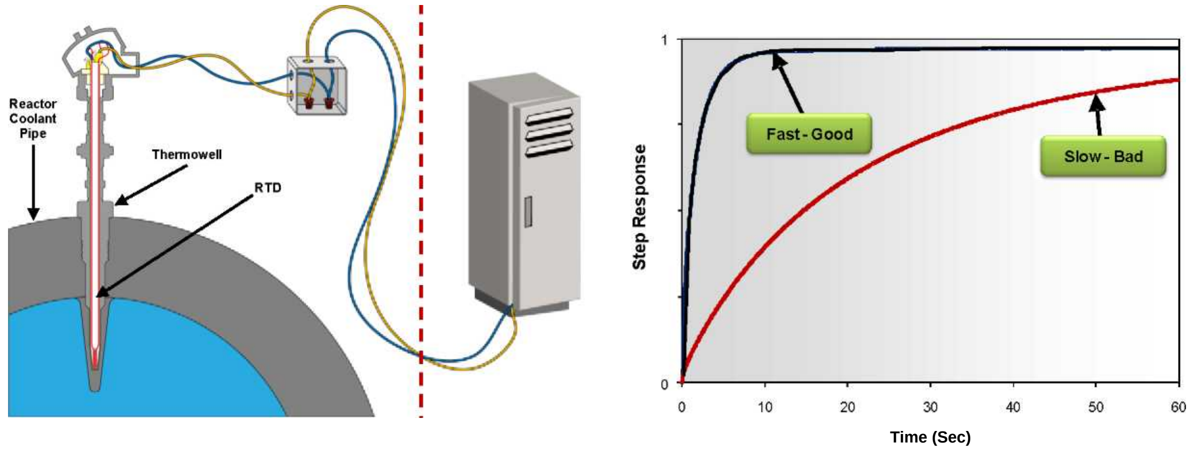

FIG. 2. Temperature Sensor Installation and Laboratory Response Time Data for a Slow and Fast RTD

vessels, and other components should be verified. In these applications, the sensors are bonded to a solid surface. For example, strap-on or cemented RTDs are used to measure surface temperature on pipes such as sensing lines in nuclear power plants. However, since the accurate performance of these sensors are in large part a function of their intimate contact to the surface to which they are attached, it is critical to verify that this contact is maintained. Sensors such as these are subject to long-term exposure to heat, humidity, vibration, and other process conditions which cause the bonding of these sensors to deteriorate. The sensor then becomes detached from the solid surface leaving a gap between the sensor and the bonding surface, resulting in an erroneous indication. As a result, new tests based on the LCSR method have been developed to characterize the quality of bonding between sensors such as RTDs, thermocouples, and strain gages and a solid material. Reference [2] describes how the LCSR is used for these applications.

In addition to sensor response time testing and detection of sensor-to-solid bonding, the LCSR method can be used for diagnostics of wiring and circuit problems in instrumentation systems. For example, in the early 1980s, the LCSR method was being used for thermocouple response time testing on experimental nuclear fuel assemblies at the Argonne National Laboratory (ANL). In addition to providing dynamic response information, LCSR tests identified a number of reverse-connected thermocouples. The problem was manifested in unusual LCSR transients that were obtained during the response time measurements. In another instance, NASA rocket nozzle thermocouples were also determined by the LCSR test to be reversely connected; an event similar to that of ANL. Then again in the same NASA project, the LCSR method was used to identify thermocouples whose measuring junctions were not at the tip of the thermocouple, as they would be normally. These problems would have resulted in erroneous temperature measurements in a very important application [3].

In the LCSR test, a step change signal in current is sent to the RTD sensing element, which causes the sensor to heat internally. The test is performed by connecting the RTD to a Wheatstone resistance bridge. The bridge includes a switch that allows the electrical current through the RTD to be switched from 1 or 2 mA to 30 to 50 mA for the test. This internal heating causes a transient increase in the RTD resistance that manifests itself as an exponential transient at the Wheatstone bridge's output. This transient is recorded and analyzed to identify the RTD's response time. Because it takes into account the effects both of installation and process conditions on response time, the LCSR method represents a significant step beyond traditional age-testing techniques for nuclear plant temperature sensors.

Active measurement or test signal-based predictive maintenance methods also include the time domain reflectometry (TDR) test. It is used to locate problems along a cable, in a connector, or at an end device by sending a test signal through the conductors in the cable and measuring its reflection. The TDR technique has also served the nuclear power industry in testing instrumentation circuits, motors, heater coils, and a variety of other components. In a TDR test, a step signal is sent through the cable, and its reflection is plotted versus time. The plot will show any changes in impedance along the cable, including at the end of the cable. If the TDR is trended, problems that may develop along the cable or at the end device can be identified and located. The simplest application of TDR is locating an open circuit along a cable or in an end device (e.g. RTD) as shown in Figure 3. It is possible to tell if the circuit is open by measuring its loop resistance, but only a TDR would indicate where the circuit is open. A complementary set of cable tests, LCR testing, is often used in addition to TDR to identify whether a circuit problem is caused by an open circuit, short circuit, shunt, moisture intrusion, or other age-related problems. The LCR test is performed by measuring and trending the inductance (L), capacitance (C), and resistance (R) of a cable or circuit.

Distance (Feet)

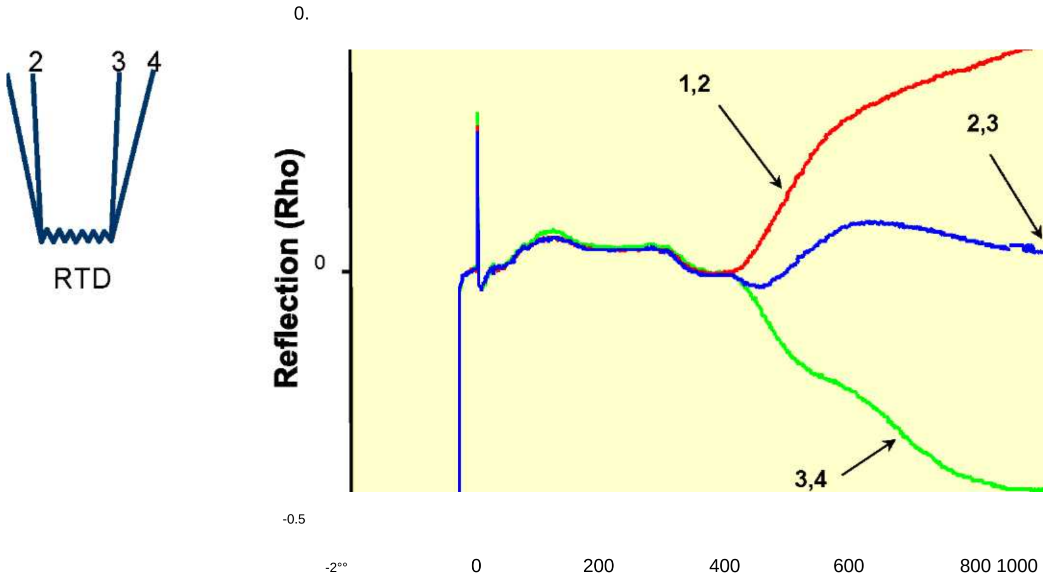

Fig. 3. Time Domain Reflectometry (TDR) Trace Showing an RTD Open Circuit (Nuclear Plant Data)

The combination of TDR, LCR, and LCSR tests has proved very effective in separating cable problems from sensor problems in RTDs, thermocouples, and strain gauges. As for other nuclear plant sensors such as neutron detectors, the combination of TDR, LCR and the noise analysis technique are used to verify the integrity of the cables and performance of the end device, in this case, the neutron detector.

3. MONITORING THE PERFORMANCE OF NUCLEAR PLANT PRESSURE TRANSMITTERS

Accuracy and response time are two of the most important indicators of performance of a pressure sensing system like the one shown in Figure 4. As such, on-line methods have been developed to monitor the calibration and response time of pressure transmitters in nuclear power plants. For on-line measurement of response time of pressure transmitters, the noise analysis technique is used as described in [3]. This method is based on recording the random noise, which exists naturally at the output of most process sensors while the plant is operating. The noise can be analyzed in the frequency domain and/or time domain to give the response time of the transmitter. As documented in [3], this method has been validated for response time testing of pressure, level, and flow transmitters in nuclear power plants. Impulse lines (also called sensing lines) are the small tubes which bring the pressure signal from the process to the sensor. Typically, the length of an impulse line is 30 to 300

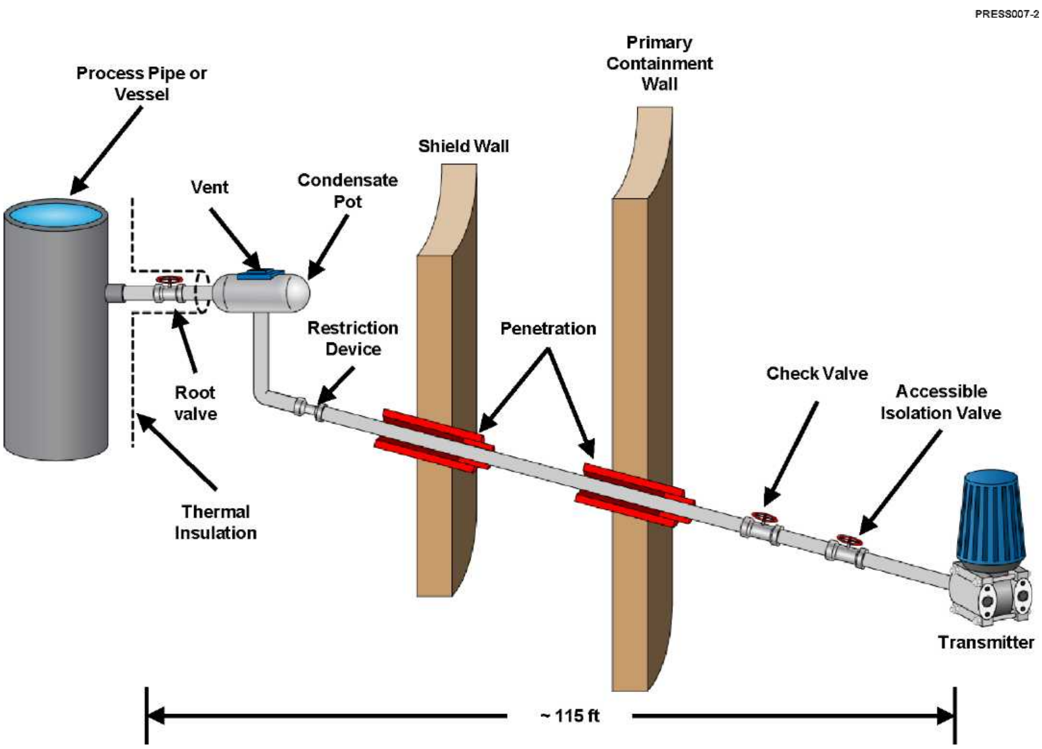

Fig. 4. Sensing Line Connecting a Pressure Transmitter to the Process

meters, depending on the service in the plant, and there are often isolation valves, root valves, snubbers, or other components on a typical impulse line (Figure 4). The malfunction in any valve or other component of the impulse line can cause partial or total blockage of the line. In addition, and more importantly, impulse lines can become clogged due to sludge and deposits that often exist in the reactor coolant system. The clogging of sensing lines can cause a delay in sensing a change in the process pressure, level, or flow. In some plants, sensing line clogging due to sludge or valve problems has caused the response time of pressure sensing systems to increase from 0.2 seconds to 5 seconds. This problem can be identified while the plant is on-line using the noise analysis technique as described in [4]. Basically, if the response time of the pressure, level, or flow transmitter is measured with the noise analysis technique, the results will include any delay due to the sensing line length, any blockages, voids, and other restrictions. Figure 5 shows the effects of air in the pressure sensing lines of pressure transmitters on an auto power spectral density (APSD) using noise analysis.

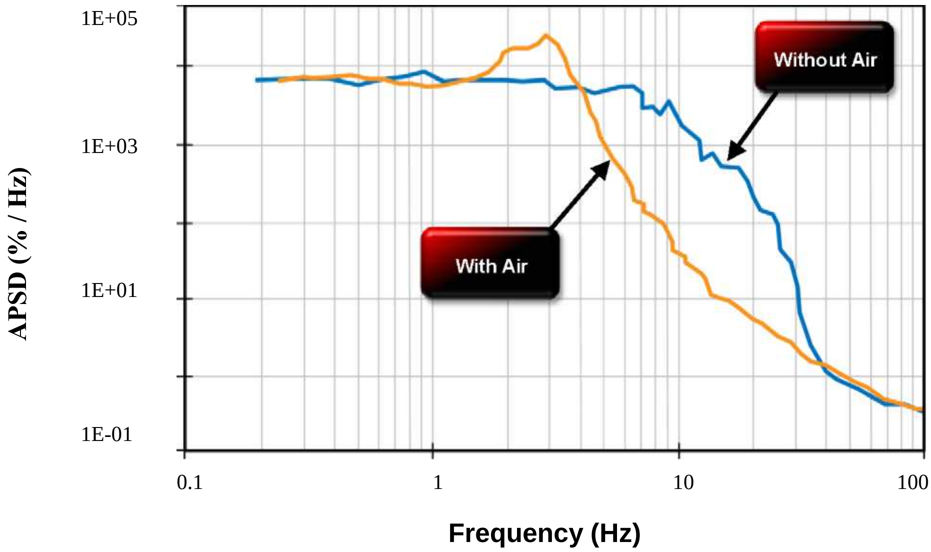

Fig. 5. Auto Power Spectral Density (APSD) Plots With and Without Air in the Pressure Sensing Line of Rosemount Pressure Transmitter (Laboratory Data)

4. ON-LINE MONITORING AND CALIBRATION

Calibration of temperature, pressure, and other important sensors in nuclear power plants is performed once every fuel cycle, which is typically one or two years. Calibration is essential to ensure safe and reliable operation of the plant. These calibration activities require significant resources and time in order to isolate the instruments, calibrate them, and return them back to full service. However, recent studies of the calibration histories of these process instruments have shown that high quality sensors maintain accurate measurements for more than a year or two and, therefore, do not need calibration that often [5] [6]. This opportunity for using of performance based calibration rather than simply time based calibration led to the development of many of the on-line drift monitoring and cross calibration techniques referenced in this paper.

On-line calibration monitoring is the monitoring of normal process instruments during plant operation and comparing the data with an estimate of the process parameter that the instrument is measuring. The process parameter estimate may be obtained using a variety of methods, although two are specifically discussed herein.

4.1 Averaging Technique

With this method, redundant sensor outputs are monitored during process operation to identify drift with respect to the process parameter estimate (e.g. average). If the sensor drift is outside of prescribed limits, the sensor is re-calibrated. Otherwise, the sensor is not calibrated or calibrated less often. This method is applicable to all types of process sensors; however, the best application is for calibration verification of pressure, level, and flow transmitters.

4.2 Analytical Modelling Technique

The analytical modelling approach for detecting instrument drift requires an independent estimate of the monitored process. This estimate is then tracked and compared to the indication of the instruments. A number of analytical techniques are available to help obtain an independent estimate of process parameters. These are categorized as either empirical or physical modelling techniques. Each technique estimates the value of the process parameter based on other related parameters. For example, in a contained boiling process, temperature and pressure are related by the laws of physics. Consequently, as a specific temperature in this process is measured, a corresponding pressure can be easily calculated, tracked, and compared with the "measured pressure" as a reference to identify systematic drift. This approach can also be used to provide a reference for detecting drift if there is no redundancy or to add to existing redundancy. With this approach, the calibration drift of even a single instrument can be tracked and verified on-line. In essence, a redundant analytical sensor can be created by using these modelling techniques and/or used as a reference for detecting drift. The boiling example above is very simple, and in practice, process parameters cannot always be identified by measuring a single parameter. For example, in physical modelling, complex relationships are often involved in relating one parameter to another. Furthermore, a fundamental knowledge of the process and material properties is often required to provide reliable estimates of a parameter using a physical model. As such, empirical models are often preferred for parameter estimation for on-line calibration verification. However, even empirical models normally use multiple inputs to produce a single output or multiple outputs. In some cases, complex empirical equations, neural networks, pattern recognition, and sometimes a combination of these techniques, including fuzzy logic for data clustering are required [7]. Generally, for these advanced techniques, the model is first trained under a variety of process operating conditions and then used for on-line monitoring.

5. ON-LINE CALIBRATION MONITORING SYSTEM

The conceptual design of an on-line calibration monitoring system is shown in Figure 6. This conceptual system uses the process estimation techniques of averaging of redundant signals, empirical modeling, and physical modeling. Initially, the raw data is screened by a data qualification algorithm and then analyzed to provide an estimate of the process parameter being monitored. In the case of averaging analysis, the data is first checked for consistency. The consistency algorithm looks for reasonable agreement between redundant signals. Signals that fall too far away from the other redundant signals are excluded from the average or are weighted less than the signals that agree well with each other.

On-line monitoring data may be obtained directly from the plant computer or a dedicated data acquisition system. As on-line monitoring data is received, it can be readily analyzed or stored for subsequent analysis as needed. Normally, on-line monitoring data would be retrieved from the plant computer, stored on a computer disk, and analyzed to generate a table of results. The calibration status of each transmitter would be identified in the table as either "good" or "bad" depending on whether or not the transmitter met the requirements for drift. Only those transmitters identified as bad are then calibrated in the ensuing refuelling outage.

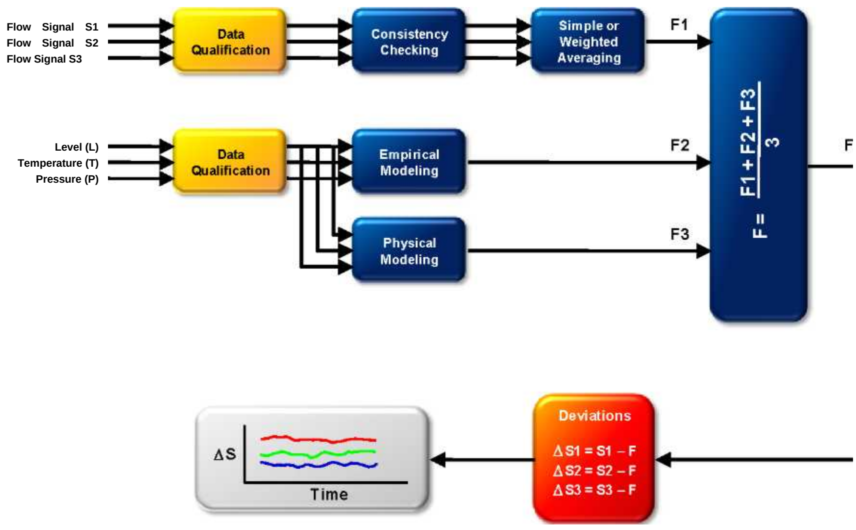

FIG. 6. Conceptual Design of an On-Line Calibration Monitoring System

The on-line calibration monitoring techniques described above are typically performed during steady state conditions (i.e., constant process operating conditions). As such, this approach may be considered a single-point calibration check. However, in order to verify the calibration of instruments over their entire operating range, on-line monitoring data should be collected at various operating conditions. In a nuclear power plant, this is most practical during the plant start-up and/or shutdown periods. During these periods, the instrument calibration can be verified over a wide range of conditions. An example of on-line calibration monitoring during plant start-up is shown in Figure 7. This figure shows the range of drift of one transmitter at seven different stages of plant operation compared to the allowable calibration limits of that transmitter. The drift results represent the percentage of deviation of the transmitter from the average of the other transmitters in the group (less any outlier). The dashed-lines shown in Figure 7 represent the plant's acceptance criteria for the drift of this particular transmitter.

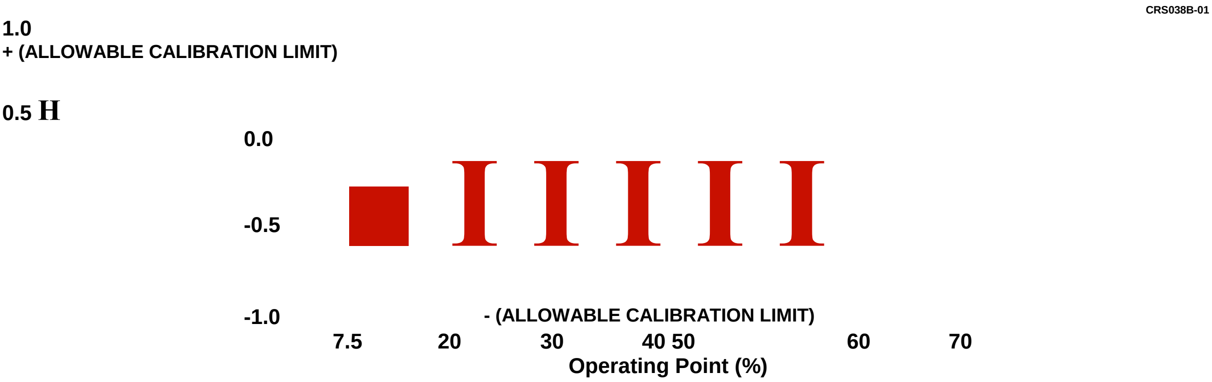

FIG. 7. On-Line Monitoring Results for Assessment of Calibration of a Pressure Transmitter as a Function of Pressure Range

6. CONCLUSIONS

Although there are significant cost-related and safety-related benefits derived from the use of OLM in nuclear power plants, many have been slow to implement these technologies. The reasons are many, but the most prominent of these is the concern over regulatory constraints.

In the year 2000, the U.S. Nuclear Regulatory Commission (NRC) issued a Safety Evaluation Report (SER) accepting the OLM concept for condition-based calibration of safety-related pressure transmitters in nuclear power plants. However, according to this SER, each plant must still apply to the NRC for approval for OLM implementation to replace traditional calibration of safety-related equipment. This is, of course, a hindrance for OLM and has slowed its widespread use in the nuclear industry. Efforts are now underway, though, with representatives of the U.S. nuclear industry and nuclear power plant vendors to obtain generic NRC licensing for the use of OLM in nuclear power plants. If approved, generic licensing will allow nuclear power plants to implement OLM without having to apply for an individual license for each plant.

REFERENCES

[1] "Long Term Performance and Ageing Characteristics of Nuclear Plant Pressure Transmitters." US Nuclear Regulatory Commission, NUREG/CR-5851, March 1993.

[2] "Effects of Ageing on Response Time of Nuclear Plant Pressure Sensors." US Nuclear Regulatory Commission, NUREG/CR-5383, June 1989.

[3] "Loop Current Step Response Method for In-Place Measurement of Response Time of Installed RTDs and Thermocouples," (American Institute of Physics) Seventh International Symposium on Temperature, 6:1151-1156, Toronto, Canada, May 1992.

[4] "New Instrumentation Technologies for Testing the Bonding of Sensors to Solid Materials," National Aeronautics and Space Administration, Marshall Space Flight Center, NASA/CR-4744, May 1996.

[5] Electric Power Research Institute (EPRI), "On-line Monitoring of Instrument Channel Performance," EPRI Technical Report Number TR-104965-RI NRC SER, Palo Alto, California (September 2000).

[6] "On-Line Testing of Calibration of Process Instrumentation Channels in Nuclear Power Plants," U.S. Nuclear Regulatory Commission, NUREG/CR-6343 (November 1995).

[7] Ruan, D., Fantoni, P., "Power Plant Surveillance and Diagnostics," Paper 23, pp. 355-376, Springer-Verlag (2002).