Application of Advanced Technology to Improve Plant Performance in Nuclear Power Plants

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Abstract. Advances in computer technologies, signal processing, analytical modeling, and the advent of wireless sensors have provided the nuclear industry with ample means to automate and optimize maintenance activities and improve safety, efficiency, and availability, while reducing costs and radiation exposure to maintenance personnel. This paper provides a review of these developments and presents examples of their use in the nuclear power industry and the financial and safety benefits that they have produced.

As the current generation of nuclear power plants have passed their mid-life, increased monitoring of their health is critical to their safe operation. This is especially true now that license renewal of nuclear power plants has accelerated, allowing some plants to operate up to 60 years or more. Furthermore, many utilities are maximizing their power output through uprating projects and retrofits. This puts additional demand and more stress on the plant equipment such as the instrumentation and control (I&C) systems and the reactor internal components making them more vulnerable to the effects of aging, degradation, and failure. In the meantime, the nuclear power industry is working to reduce generation costs by adopting condition-based maintenance strategies and automation of testing activities.

These developments have stimulated great interest in on-line monitoring (OLM) technologies and new diagnostic and prognostic methods to anticipate, identify, and resolve equipment and process problems and ensure plant safety, efficiency, and immunity to accidents. The foundation for much of the required technologies has already been established through 40 years of research and development (R&D) efforts performed by numerous organizations, scientists, and engineers around the world including the author. This paper provides examples of these technologies and demonstrates how the gap between some of the more important R&D efforts and end users have been filled providing the nuclear industry with the means to meet regulatory requirements, comply with technical specification provisions, or resolve operational and maintenance issues.

Although OLM provides substantial benefits to the safety and economy of nuclear power plants, it is not widely used in the nuclear industry at this time for a number of reasons; the most important of which is regulatory constraints. In particular, the regulators must allow OLM to replace the conventional techniques for maintenance of safety-related equipment to make it worthwhile for utilities to retrofit their plants with OLM technologies. To this end, the U.S. Nuclear Regulatory Commission (NRC) issued a Safety Evaluation Report (SER) in the year 2000 accepting the OLM concept for condition-based calibration of safety-related pressure transmitters in nuclear power plants. However, according to the SER, each plant must still apply to the NRC and receive approval for OLM implementation if it is to be used in lieu of traditional calibration of safety-related equipment. This is, of course, a hindrance for OLM and has slowed its widespread use in the nuclear industry. As such, in the fall of 2008, representatives of the U.S. nuclear industry initiated an effort 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. There is no doubt that this will incentivize the industry to proceed with OLM implementation at an accelerated rate.

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

Abbreviations/Acronyms

AC	Alternating Current
A/D	Analog-to-Digital
ALWR	Advanced Light Water Reactors
APSD	Auto Power Spectral Density
BWR	Boiling Water Reactors
CET	Core Exit Thermocouple
CPSD	Cross Power Spectral Density
CVCS	Chemical and Volume Control System
DC	Direct Current
ECA	Equipment Condition Assessment
FFT	Fourier Transform
GEN IV	Generation IV
HTGR	High-Temperature Gas-Cooled Reactors
HWR	Heavy Water Reactors
IAEA	International Atomic Energy Agency
I&C	Instrumentation and Control
LWR	Light Water Reactors
NRC	U.S. Nuclear Regulatory Commission
OLM	Online Monitoring
PWR	Pressurized Water Reactors
R&D	Research and Development
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RTD	Resistance Temperature Detector
SDP	Surveillance, Diagnostics and Prognostics
SER	Safety Evaluation Report
TTFM	Transit Time Flow Measurement
VCT	Volume Control Tank

1. INTRODUCTION

At a time when companies in every industry are seeking to improve operational efficiencies in any way possible, is it conceivable that nuclear utilizes around the world are sitting on a veritable gold mine of opportunities and not realize it? As unlikely as this seems, there is reason to believe that substantial savings can be realized through proper identification and use of existing plant data. In fact, some estimates place the value of these untapped cost savings in the nuclear industry alone on the order of $10,000,000,000 per year. These savings are a direct result of improved plant reliability, extended equipment availability and increased manpower productivity. In addition, each of these improvements can be achieved while advancing the safety and security of the nuclear power plant. Furthermore, these improvements apply to not only the conventional pressurized water reactors (PWR) developed by Westinghouse and boiling water reactors (BWR) from General Electric, but apply equally well to most advanced light water reactors (LWR), heavy water reactors (HWR), high-temperature gas-cooled reactors (HTGR) and many of the generation IV (GEN IV) advanced reactor designs as well.

The techniques presented in this paper are each, methods in obtaining and applying data from existing processes and/or equipment to further the course of nuclear utilities in meeting industry needs and fully supporting IAEA programs such as 1) Management of aging facilities, 2) License renewal, and 3) Equipment life extension, and others as well.

Although the implementation of these advanced technologies for improving plant performance may seem obvious if not at least enticing, to date, few nuclear utilities have undertaken to pursue many of these tools. For example, even though the U.S. Nuclear Regulatory Commission (NRC) has approved the use of on-line-monitoring (OLM) by issuing a Safety Evaluation Report (SER) in 2000, procedural red tape has made many reluctant to pursue it. Others have taken a more "wait and see" posture in wanting to be the first to be second. In the meantime, millions of dollars in savings are being squandered through inaction.

This paper is written with the intent of renewing the commitment for applying advanced technology to improve plant performance in nuclear power plants by addressing the following:

1. What information is available for applying advanced technology in nuclear plants?
2. How can these resources be tapped?
3. What specific applications are available for implementation of advanced technology to improve nuclear plant performance?

2. WHAT INFORMATION IS AVAILABLE FOR APPLYING ADVANCED TECHNOLOGY IN NUCLEAR PLANTS?

As people age, they tend to seek out the advice of the family doctor more frequently. The doctor will often suggest testing to help determine the health condition of the patient and as necessary prescribe medicine to counter the effects of aging or possibly the lack of personal maintenance. These steps fall in line with the familiar terms of 1) surveillance – performing tests, 2) diagnostics - making an assessment and, 3) maintenance - taking prescribed medicine. In fact, as we age further, we may even be interested to know how much longer our failing hip will last or maybe how long we could be expected to live. This is essentially prognostics or determining the remaining useful life. It is clearly evidenced that as individuals take better care of their health, the longer they live.

This is equally true with nuclear power plants. As these facilities and equipment age, the need for surveillance, diagnostics and prognostics increases. And, although not everything ages according to a set timeline, it is safe to say that most things will eventually follow the pattern of the "bathtub curve" (Figure 1).

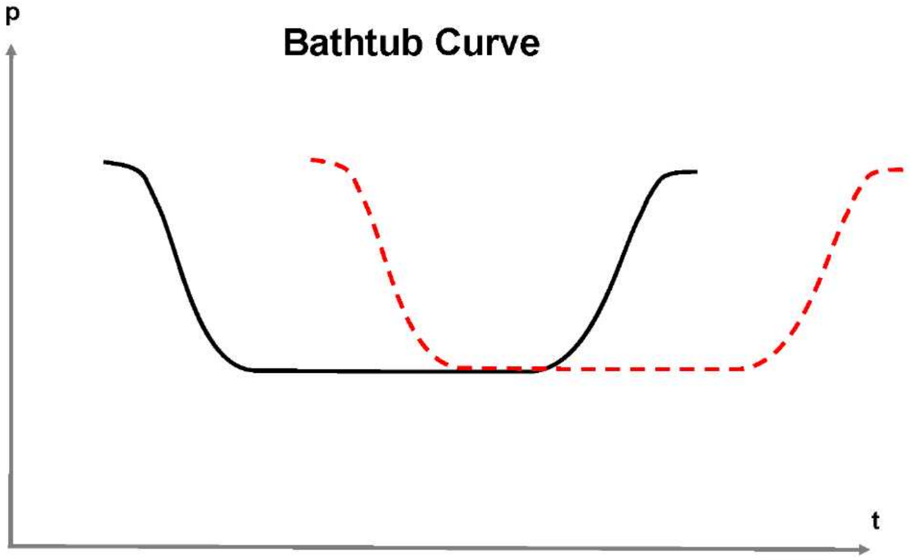

Fig. 1. Bathtub Curve Model for Reliability

As illustrated above, problems with reliability typically reveal themselves either at the beginning of the life cycle or near the end. Therefore, as shown with the dotted line, early replacement of healthy equipment is more likely to increase the probability of failure than it is to reduce this probability. Consequently, fully utilizing capital equipment not only improves the financial bottom line, but it also improves safe and reliable operations. However, without sufficient and accurate information or as in the case of the doctor, medical advice; it is difficult, if not impossible to reliably determine the remaining useful life of equipment let alone diagnose the onset of trouble.

This example points out the urgent need for reliable and accurate sources of data. As this data is identified and understood through proper surveillance, it will reveal the path to improved diagnostics, predictive maintenance and prognostics as well.

3. HOW CAN THESE RESOURCES BE TAPPED?

The question remains. Where is this data? Actually it is all around us in a nuclear power plant environment. Equipment and process performance monitoring, essentially boils down to collecting and analyzing data from sources that already exist. For example, the sensors that are used to measure process parameters such as pressure level, flow and neutron flux can also be used for surveillance, diagnostics and prognostics (SDP). Examples of these sensors within a pressurized water reactor (PWR) are show in Figure 2, although similar sensors could be found in boiling water reactors (BWR), advanced light water reactors (ALWR), Heavy water reactors (HWR), and Gen IV reactors.

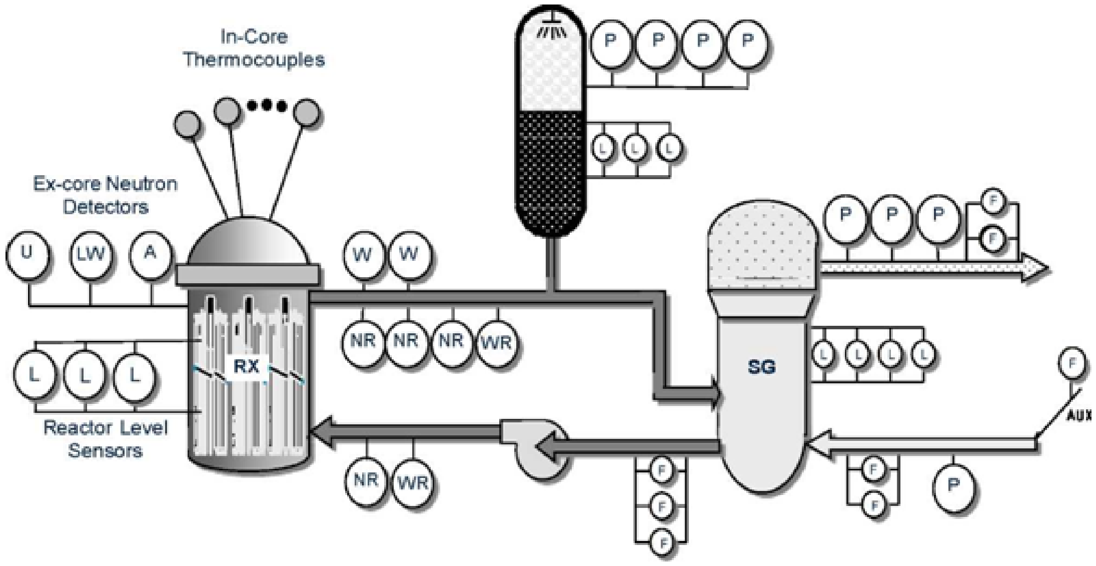

Fig. 2. Primary loop of a pressurized water reactor (PWR)

In some plants this data can be retrieved directly from the plant computer, but in most cases the sampling rate is too low for data to be useful or else the data is not collected and stored in a way that is useful. However, simply by increasing the sampling rate of existing sensors and managing this data for future retrieval, a wealth of information becomes available to the plant personnel.

One reason for increasing the sampling rate of process sensors is simply for improved resolution of the data. As shown in Figure 3, it is possible that process anomalies could go undetected as a result of low sampling rates. In other words, rapid fluctuations in process parameters could be missed due to the lack of sufficient data.

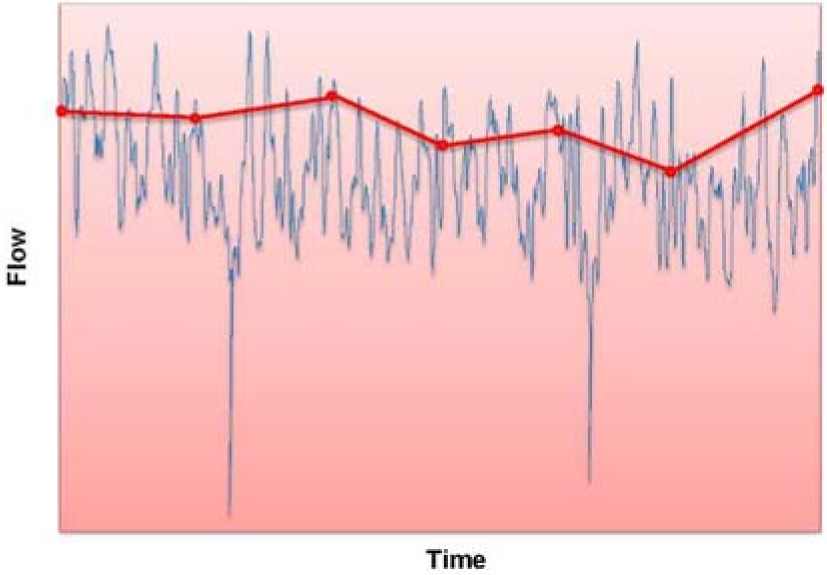

Fig. 3. Sensor Data from Low sampling Rate vs. High Sampling Rate

Another compelling reason, however, is that by increasing the rate at which the data is collected and stored, new avenues for data analyses are opened for use. Figure 4, reveals that while all sensors provide low frequency (Static) data which relate to the calibration of the sensors, they also contain high frequency (Dynamic) data which relates to response time of the particular sensor. The high frequency signal, which is known as the signal's dynamic component, stems from inherent fluctuations in the process parameter due to turbulence, random flux, random heat transfer, vibration, and other effects. The dynamic component is also referred to as the *AC signal or the noise output of the sensor* and its analysis constitutes the field of *noise analysis*.

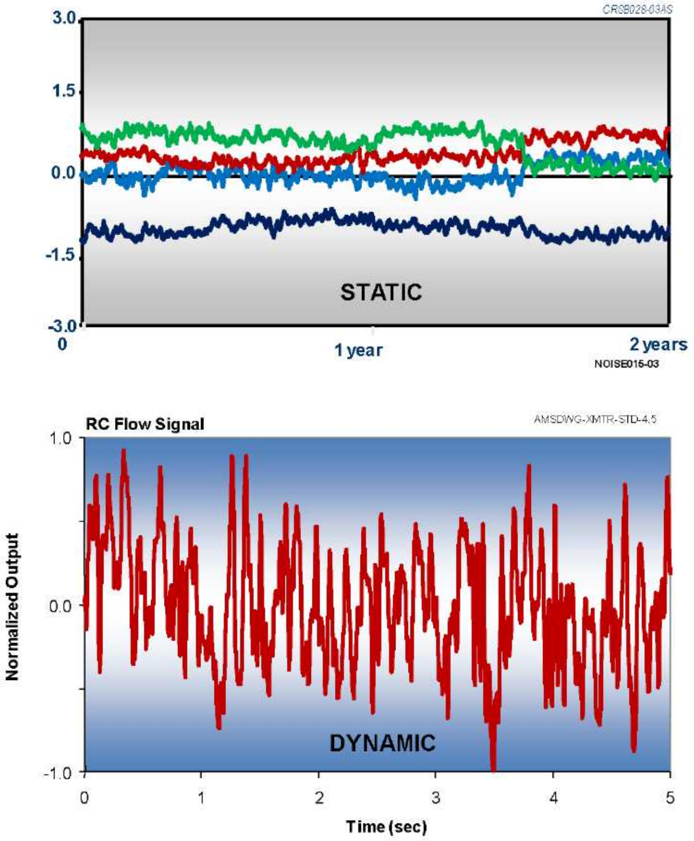

Fig. 4. Static vs. Dynamic (Noise) Sensor Data

Applications that monitor for gradual changes in the process over the fuel cycle, such as sensor calibration monitoring, make use of the static component. On the other hand, applications that monitor fast-changing events, such as core barrel motion, use the information in the dynamic component that provides signal bandwidth information. Figure 5 outlines how existing data from process sensors is used to satisfy these applications. Note in this figure that the static data is analyzed using empirical and physical modeling and averaging techniques involving multiple signals, while dynamic data analysis involves time domain and frequency domain analysis involving single signals or pairs of signals. For example, dynamic response time of a nuclear plant pressure transmitter is identified by fast Fourier transform (FFT) of the noise signal. The FFT yields the auto power spectral density (APSD) of the noise data from which the transmitter response time is calculated. In applications where pairs of signals are used (e.g. core barrel vibration measurements), the cross power spectral density (CPSD), phase, and coherence data are calculated to distinguish the vibration characteristics of various constituents of the reactor internal.

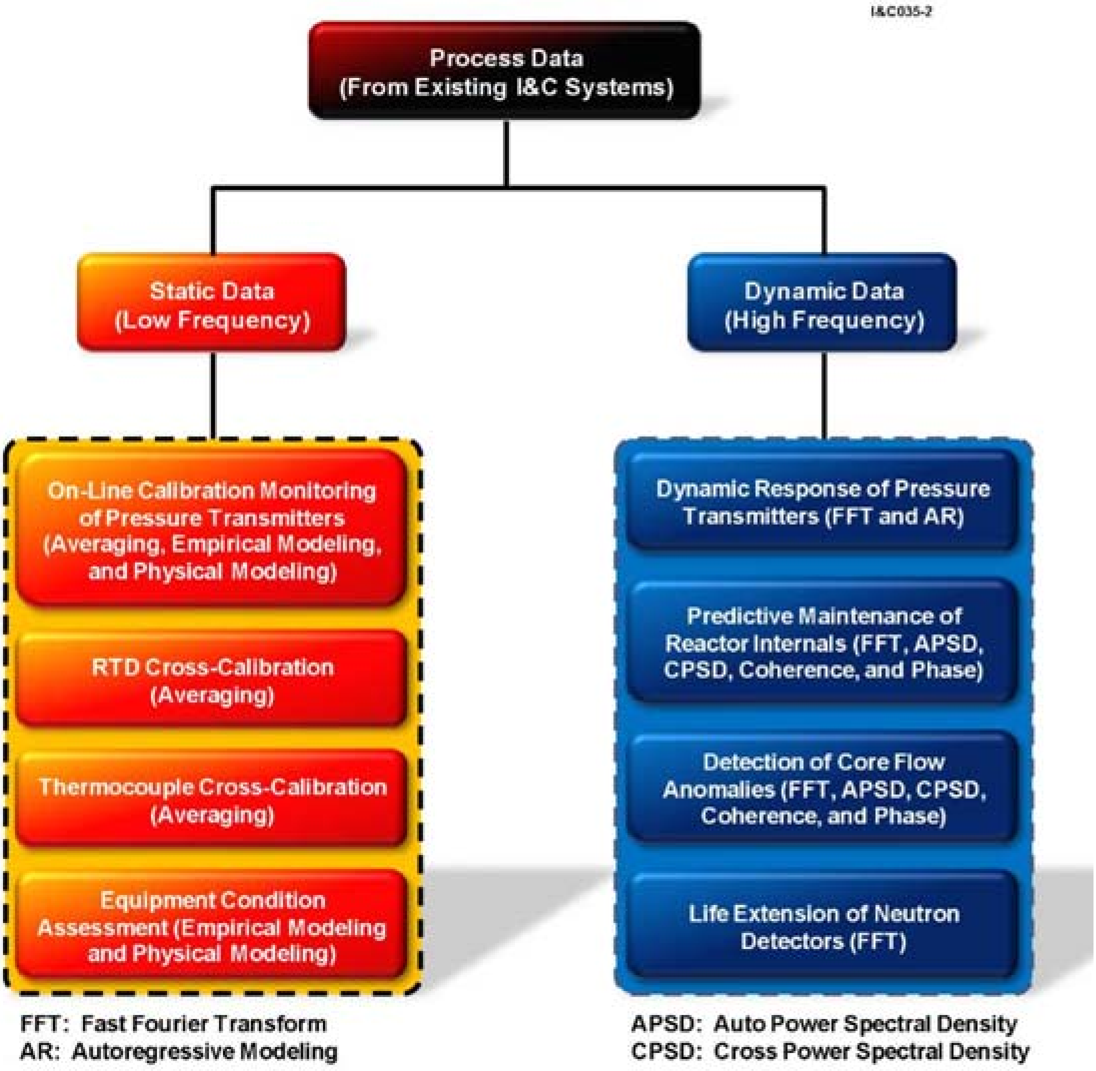

Fig. 5. On-line monitoring applications of static and dynamic data analysis

Together these static and dynamic signals can be harnessed through the use of advanced analytic techniques by applying on-line monitoring. The term on-line monitoring (OLM) is used to describe methods for evaluating the health and reliability of nuclear plant sensors, processes, and equipment from data acquired while the plant is operating. The types of OLM applications in nuclear power plants are in large part determined by the sampling rates available for data acquisition. Static OLM applications, such as resistance temperature detector (RTD) cross-calibration and on-line calibration monitoring of pressure transmitters, typically require sampling rates up to 1 Hz, while dynamic OLM applications such as sensor response time testing use data sampled in the 1 kHz range. Other OLM applications, such as vibration measurement of rotating equipment and loose parts monitoring, may use data sampled at up to 100 kHz.

4. WHAT SPECIFIC APPLICATIONS ARE AVAILABLE FOR IMPLEMENTATION OF ADVANCED TECHNOLOGY TO IMPROVE NUCLEAR PLANT PERFORMANCE?

4.1. Equipment condition assessment

In addition to evaluating the health of individual sensors, static analysis methods may be used for other purposes. Equipment condition assessment (ECA) applications take the idea of on-line calibration monitoring a step further by monitoring for abnormal behavior in a group of sensors as a means for indicating nuclear plant equipment or system malfunctions. An example of ECA is illustrated in Figure 6, which shows a simplified diagram of a typical chemical and volume control system (CVCS) in a PWR. The primary functions of a typical CVCS in a PWR are:

1. Controlling the volume of primary coolant in the reactor coolant system (RCS)
2. Controlling of chemistry and boron concentration in the RCS
3. Supplying seal water to the reactor coolant pumps (RCPs)

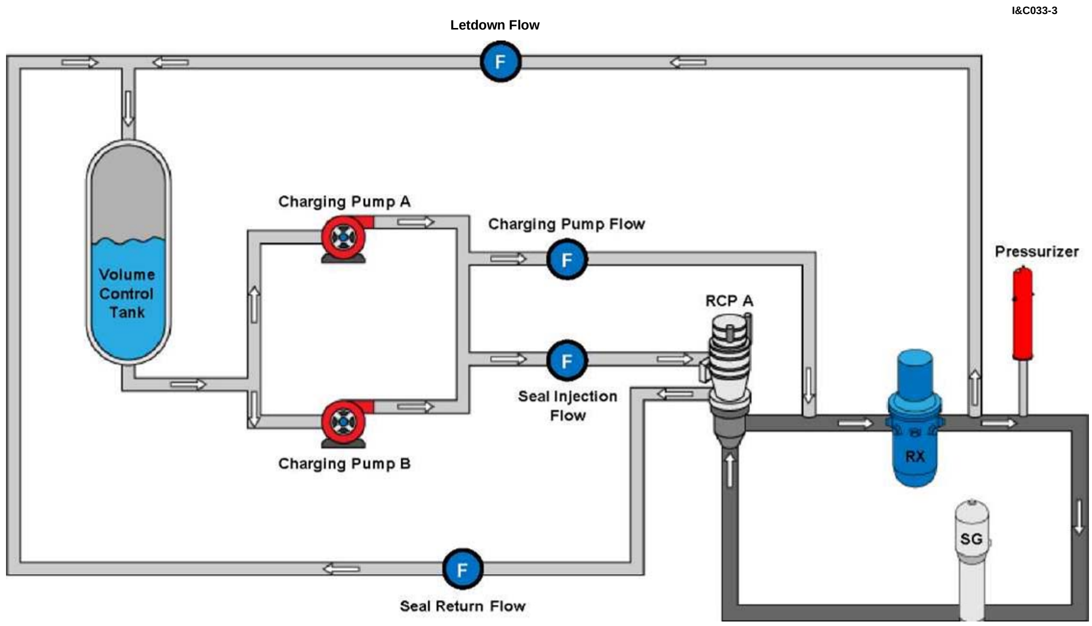

Fig. 6. Simplified diagram of chemical and volume control system components

Several transmitters are typically used to monitor various parameters related to the operation of the CVCS. Figure 6 highlights the normal operation of a few of the parameters that are monitored in the CVCS system:

1. Charging Flow - measures the flow rate of the coolant being provided from the volume control tank (VCT) to the RCS and RCP seals
2. Reactor Coolant Pump Seal Injection Flow - measures the flow rate of the coolant provided to the RCP seals
3. Seal Return Flow - measures the flow rate of the coolant returned to the VCT from the RCP seal injection
4. Letdown Flow - measures the flow rate of the reactor coolant as it leaves the RCS and enters the VCT

During normal operation, the measurements of these parameters will fluctuate slightly, but should remain at a consistent relative level. However, in abnormal conditions such as a RCP seal leak, some parameters may exhibit trends in the up or down directions indicating a problem in the plant. For example, Figure 7 shows the four flow signals mentioned above during normal operation of a PWR plant. In this figure, the actual flow rates have been scaled to simplify this example. As shown in the figure, the flows remain at relatively constant rates relative to one another.

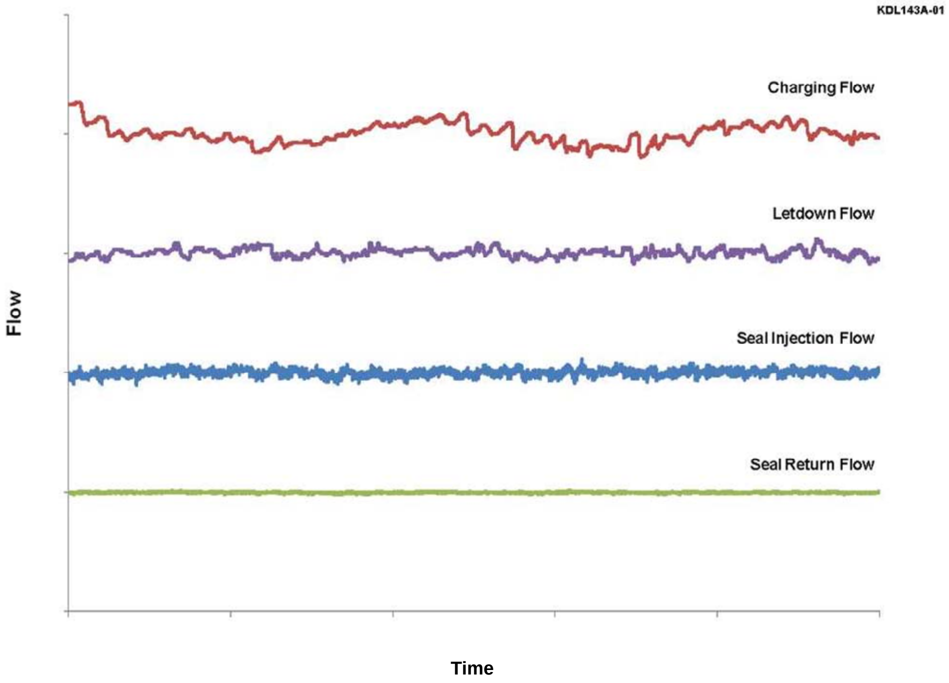

Fig. 7. Normal operation of chemical and volume control system flow parameters

Figure 8 shows how these flow signals may appear at the onset of a RCP seal leak in this PWR plant. In this example, the onset of the RCP seal leak is first indicated by a downward trend in the seal return flow measured at time T1. This is followed by an increase in charging pump flow at time T2 as the charging pump compensates for the loss of coolant due to the RCP seal leak.

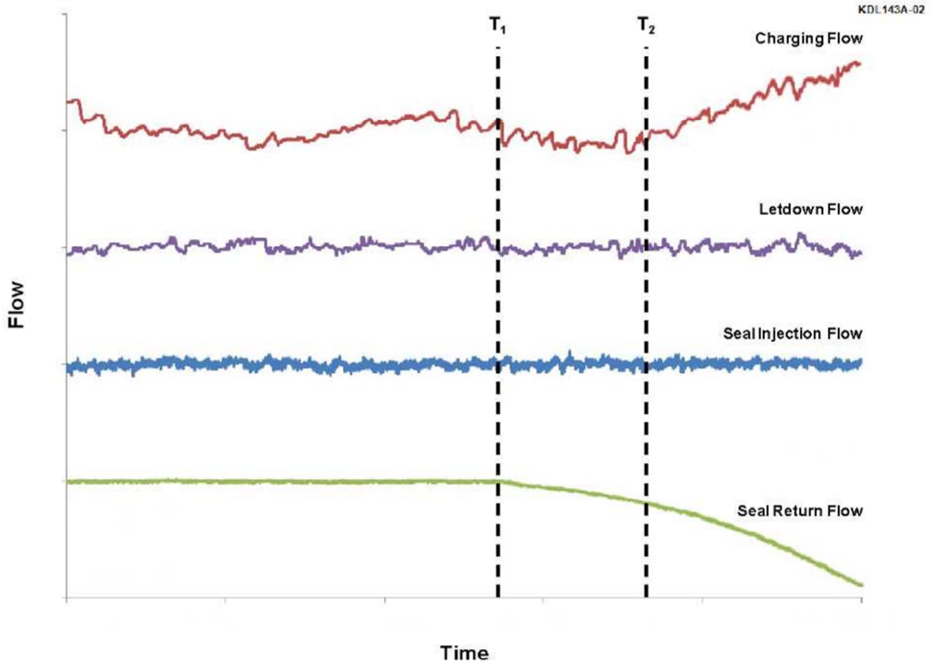

Fig. 8. Chemical and volume control system flow parameters at the onset of a reactor coolant pump seal leak

Of course, an abnormal trend in an individual parameter such as seal return flow could mean that the sensor is degrading; however, abnormalities in related parameters that occur close in time are more likely to indicate the onset of a system or equipment problem. Early warning of these types of failures is thus the key benefit of ECA. More specifically, early warning of impending equipment failures can provide nuclear plants with:

- Increased plant safety by early recognition of equipment failures
- Reduced downtime from timely repair of affected equipment

4.2. On-line detection of sensing line blockages

Chief among applications of noise analysis in nuclear power plants is detection of sensing line blockages (see Figure 9). Sensing lines (also called impulse lines) are small diameter tubes which bring the pressure signal from the process to the pressure sensor. Depending on the application and the type of plant, pressure sensing lines can be as long as 300 meters or as short as 10 meters. They have isolation valves, root valves, and bends along their length making them susceptible to blockages from residues in the reactor coolant, failure of isolation valves, and other problems. Sensing line blockages are a recurring problem in PWRs, boiling water reactors (BWRs), and essentially all water-cooled nuclear power plants. It is an inherent phenomenon which causes the sensing lines of nuclear plant pressure transmitters to clog up with sludge, boron, magnetite, and other contaminants. Typically, nuclear plants purge the important sensing lines with nitrogen or back fill the lines periodically to clear any blockages. This procedure is, of course, time consuming and radiation intensive, and more importantly, not always effective in eliminating blockages. Furthermore, except with the noise analysis technique, there is no way to know ahead of time which sensing lines may be blocked. Also, without the noise analysis technique, it is not possible after purging or back filling a sensing line to verify that the line has been cleared.

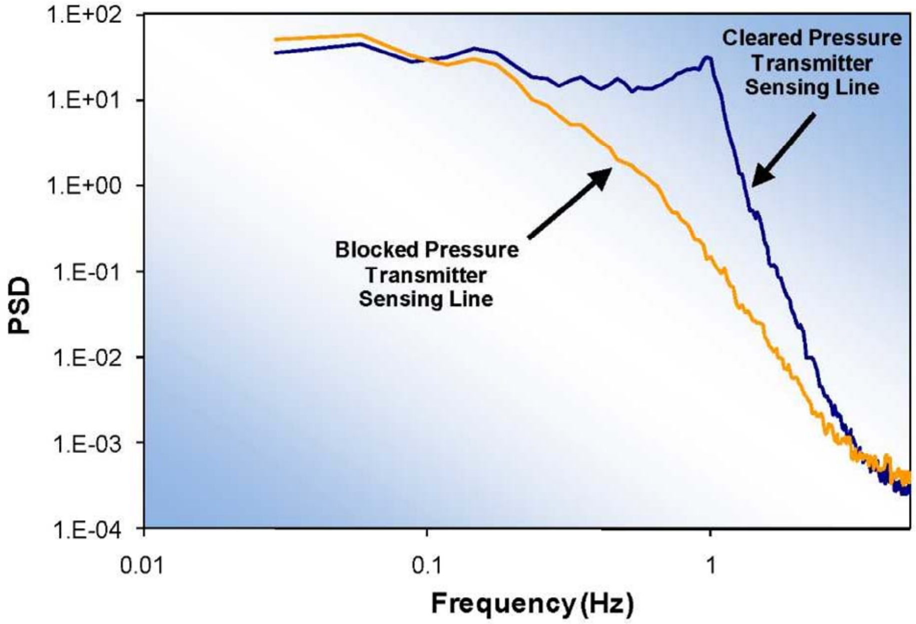

Fig. 9. On-line monitoring applications of static and dynamic data analysis

Figure 10 presents a photograph that shows the cut-away of a partially blocked sensing line of a nuclear power plant pressure transmitter. It is apparent that this blockage can reduce the flow path in this sensing line by about 40 percent. A blockage like this is detrimental to dynamic response of the pressure sensor located at the end of the sensing line. In particular, depending on the design characteristics of the pressure transmitter, a sensing line blockage like this can cause the response time of the affected pressure transmitter to increase by an order of magnitude. The degree of increase in the dynamic response depends on the "compliance" of the pressure transmitter. Compliance is a pressure transmitter design parameter which relates to the physical displacement of the sensing element of the transmitter per unit of input pressure. Some transmitters such as those with sensing elements made of "bellows" have a large compliance and are therefore affected strongly by sensing line blockages. On the other hand, transmitters with sensing elements made of stiff diaphragms have smaller compliances and are therefore less affected by sensing line blockages.

The effect of compliance on dynamic response of a pressure transmitter was uncovered in a research project performed by the author for the U.S. Nuclear Regulatory Commission (NRC) in the early 1990s [1]. The goal of the project was to characterize the effects of normal aging on performance of nuclear plant pressure transmitter.

Blockage of sensing lines obviously renders the pressure sensor essentially useless or even dangerous. The danger here is that, due to a total blockage, the operating pressure may get locked in the transmitter and cause its indication to appear normal. Then, when the pressure changes, the transmitter will not respond and will continue to show the locked-in pressure which will certainly confuse the reactor operators and can pose a risk to the safety of the plant.

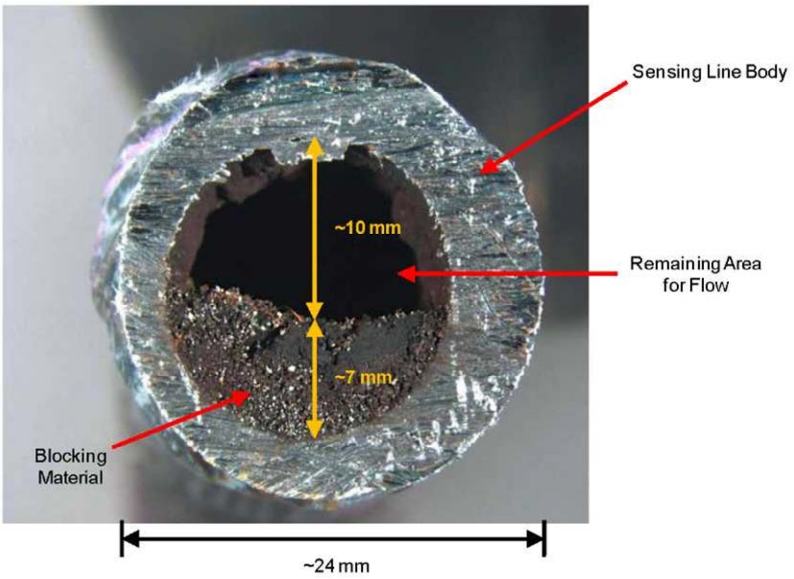

Fig. 10. Photograph of a nuclear plant sensing line with a partial blockage

If a blocked pressure transmitter happens to be a part of a redundant safety channel, it can trip the plant during a transient. More specifically, the indication of a blocked transmitter will obviously not match the other redundant channels creating a mismatch that could trigger a reactor trip. In fact, this problem has occurred in France where partial blockages in flow transmitters caused two French PWRs to trip during load flowing episodes [2].

It is unfortunate, that even today; some nuclear power plants measure the response time of their safety-related pressure transmitters using conventional procedures that do not include the sensing lines in the measurement. These plants typically use a hydraulic pressure generator to input a pressure signal to the transmitter and measure its response time. In doing this, the sensor is isolated from the sensing lines. The research work documented in NUREG/CR-5851 [1] uncovered this flaw in the maintenance of nuclear plant pressure transmitters. Therefore, many plants have recognized that they must measure the response time of not only their pressure transmitters but also their sensing lines. As a result, these plants have switched to the noise analysis procedure to verify the dynamic characteristics of their pressure sensing systems.

4.3. Predictive maintenance of reactor internals

Typically, vibration sensors (e.g. accelerometers) are located on the top and bottom of the reactor vessel to sound an alarm in case the main components of the reactor system vibrate excessively. However, neutron detectors have proven to be more sensitive in measuring the vibration of the reactor vessel and its internals than accelerometers. This is because the frequency of vibration of reactor internals is normally below 30 Hz, which is easier to resolve using neutron detectors than accelerometers. Accelerometers are more suited for monitoring higher-frequency vibrations.

Figure 11 shows the APSD of the neutron signal from an ex-core neutron detector (NI-42) in a PWR plant. This APSD contains the vibration signatures (i.e., amplitude and frequency) of the reactor components, including the reactor vessel, core barrel, fuel assemblies, thermal shield, and so on. It even contains, at 25 Hz, the signature of the RCP rotating at 1,500 revolutions per minute, which corresponds to 25 Hz. These signatures can be trended to identify the onset of aging degradation that can cause damage to the reactor internals. This approach has been recognized as a predictive maintenance tool that can help guard against vibration-induced mishaps that may be encountered as plants age and become more vulnerable to challenges to their structural integrity.

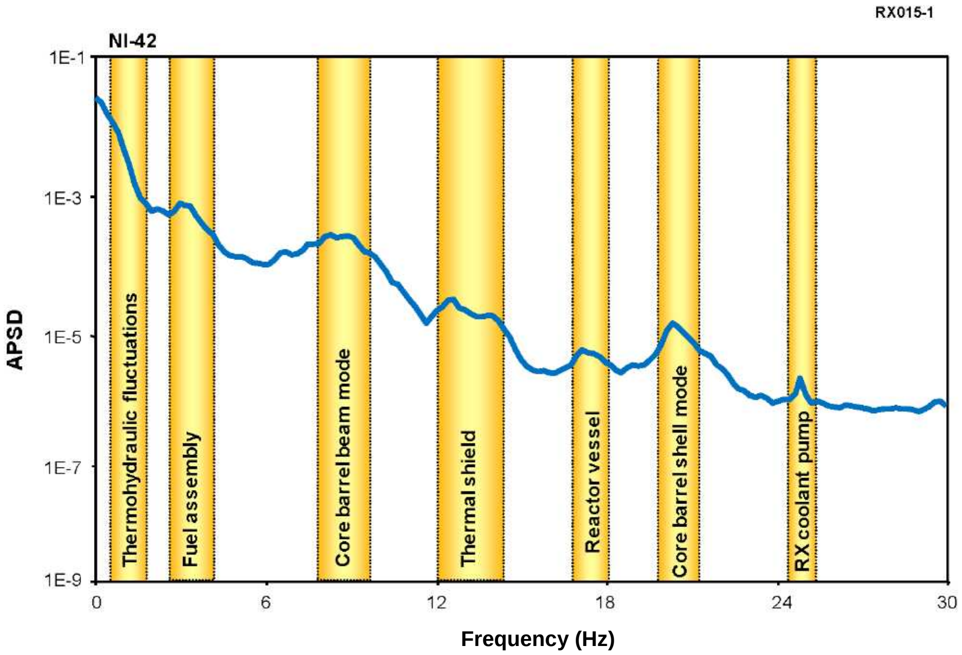

Fig. 11. Auto power spectral density containing vibration signatures of reactor internals

Over the last ten years, the author has successfully promoted the noise analysis technique for management of aging of a variety of nuclear plant equipment including the reactor internals. As a result, numerous plants have embarked on a program of measurement of reactor internal vibration using neutron noise analysis and trending of the results to identify changes and to look for signs of degradation.

4.4. OLM system development

The research efforts documented in NUREG/CR-6343 [3] and NUREG/CR-5851 [1] have helped provide the foundation for developing an OLM system to verify the static and dynamic performance of nuclear plant I&C systems. The OLM system would consist of a data acquisition module and a data analysis module. The data acquisition model should include signal isolation devices as well as fast sampling capabilities (e.g. 1000 Hz). If the data sample rate is high, it can be used for calibration verification by DC signal analysis using averaging and modeling techniques, and response time testing by AC signal analysis using the noise analysis technique.

OLM technologies can cover other applications such as neutron noise analysis for measurement of vibration of reactor internals and other components such as RCPs and cross correlation of neutron signals with other sensors such as CETs in a PWR plant to monitor flow and detect flow anomalies.

5. OLM SYSTEM FOR NUCLEAR POWER PLANTS

An OLM system is made up of a data acquisition module involving hardware and software and a data processing module involving software implemented on a fast computer. The system can be built into the design of new plants or deployed as an add-on feature to the existing generation of plants.

A fundamental requirement for an OLM system is a fast data acquisition module. In the current generation of nuclear power plants, data from process sensors is normally sampled by the plant computer at rates of one sample per second or slower. This is adequate for applications such as calibration monitoring but not for dynamic analysis. For analysis of dynamic signals, at least 100 to 1000 samples per second are normally required. In the new generation of nuclear power plants, this requirement can be accommodated simply by bringing the data into the plant computer through a fast analog-to-digital (A/D) converter and providing adequate storage to save the data for subsequent retrieval and analysis. However, in the existing generation of reactors, it is not simple to retrofit the plant with a fast data acquisition system and new storage provisions. In fact, even recent digital retrofits in nuclear power plants have not provided the necessary means for fast data collection and storage. As such, in the current generation of nuclear power plants, a separate data acquisition system must be installed for collection of dynamic data.

6. CONCLUSION

Over the last 40 years, an array of techniques has been developed for equipment and process condition monitoring. These techniques have been implemented in nuclear power plants mostly on an "as-needed" basis rather than for routine condition monitoring applications. Now, with the advent of fast data acquisition technologies and the proliferation of computers and advanced data processing algorithms and software packages, condition monitoring can be performed routinely and efficiently.

This paper provides a review of a class of condition monitoring technologies which depend on data from existing process sensors during all modes of plant operation including start up, normal operating periods, and shutdown conditions. The data may be sampled continuously or periodically depending on the application. The steady-state (DC) component of the data is analyzed to identify slowly developing anomalies such as calibration changes in process sensors. The fluctuating (AC) component of the data is analyzed to determine such parameters as response time of pressure sensors or measure the vibrational characteristics of reactor internals, check for blockages within the reactor coolant system, identify flow anomalies, and provide other diagnostics.

The AC and DC data acquisition and signal processing techniques described in this paper can be integrated together to provide an online monitoring (OLM) system for nuclear power plants. It is envisioned that such OLM systems will be built into the design of the next generation of reactors to provide automated measurements, condition monitoring, and diagnostics to contribute to optimized maintenance of the plant. As for the current generation of reactors, they would be retrofitted with OLM systems as utilities begin to appreciate their benefits and the regulators realize the added benefits of OLM to the safety of nuclear reactors. An example is the Sizewell nuclear power plant in the UK which has implemented some of the OLM technologies described here and significantly benefited from this implementation.

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