On-Line Monitoring for Calibration Extension: an Overview and Introduction

(See NUREG/CR-6895 for details)

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This document is an overview of NUREG/CR-6895. The actual guidance is contained within the three volumes of NUREG/CR-6895. No regulatory decisions or evaluations should be made on the basis of this document alone.

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Objectives and Document Organization

The three volume NUREG/CR-6895 series was developed to provide background, technical guidance and explore implementation issues related to the use of On-Line Monitoring (OLM) for the extension of safety critical sensor calibration intervals.

Volume 1, entitled "State of the Art", provides a general overview of sensor calibration monitoring technologies and their uncertainty analysis, a review of the supporting information necessary for assessing these techniques, and a cross reference between the literature and the requirements listed in the NRC Safety Evaluation Report: "Application of On-Line Performance Monitoring to Extend Calibration Intervals of Instrument Channel Calibrations Required by the Technical Specifications" which was published in 2000 [NRC Project no. 669, 2000].

Volume 2, entitled "Theoretical Issues", provides an evaluation of the application of the most commonly employed OLM methods. In empirical, model-based OLM, current measurements are applied to an algorithm that uses historical plant data to predict the plant's current operating parameter values. The deviation between the algorithm's predicted parameter values and the measured plant parameters is used to detect any instrument faults, including instrument drift. Many algorithms can be used to accomplish OLM; however, only auto-associative neural networks (AANN), auto-associative kernel regression (AAKR), and auto-associative multivariate state estimation technique (AAMSET) are presented in that report. Those techniques were chosen because they were either considered by Electric Power Research Institute's (EPRI) OLM working group that started in the 1990s, applied in EPRI's OLM Implementation Project which began in 2001, or are available as commercial products.

Volume 3 entitled "Limiting Case Studies", explore assumptions inherent in the model and other special limiting cases. The case studies reported in Volume 3 apply the modeling and uncertainty analysis techniques described in Volume 2 to a wide variety of plant data sets to consider the effects of these modeling assumptions and limitations.

The purpose of this document is to provide a summary and overview for NRC staff using the NUREG/CR-6895 series as an aid to verify conformance with the previously cited regulatory basis and standards in the acceptance of an OLM system for safety-critical sensor calibration extension. Part A provides general OLM background information. Section 1 provides a very brief introduction to OLM. Section 2 outlines the regulatory basis that applies to OLM. Section 3 describes the guidance manuscripts already available for OLM. Part B presents information related to the NRC review and approval of an OLM system. Section 1 offers a brief introduction. Section 2 presents OLM topics and issues which are critical for the implementation of an OLM system. Section 3 describes some OLM activities which should be addressed for regulatory acceptance. Finally, Section 4 examines some acceptance criteria which an OLM system should meet in order to be considered for regulatory approval.

A. OLM Background

1. Introduction

Traditionally, safety-critical process instrumentation channels are manually calibrated every time a nuclear plant has a refueling outage. During these manual calibrations, the instruments must be taken out of service and falsely loaded to simulate actual in-service conditions. "Searches of the License Event Report (LER) and Nuclear Plant Reliability Data System (NPRDS) databases as well as an informal survey of the nuclear power industry have revealed that less than 10 percent of pressure transmitters in nuclear power plants have been found in the past to drift out of tolerance" [IAEA 2008]. An EPRI study found that only 3 out of 646 sensors required recalibration when manually checked at the end of their fuel cycle [EPRI 2003]. These unnecessary maintenance procedures can result in damaged or miscalibrated equipment, can increase a plant's downtime if the maintenance task is on the critical path, and sometimes cause workers to receive a radiation dose. Furthermore, with these frequency-based calibrations, sensor conditions are only checked periodically; therefore, faulty sensors can continue to operate with a potential fault for periods up to the calibration frequency. These weaknesses associated with current calibration methods have motivated the nuclear industry to investigate alternative, less invasive, calibration techniques.

In past years, much research has focused on using on-line monitoring (OLM) to move towards condition-directed calibration. In OLM, sensor data is applied to an algorithm that estimates the true or un-faulted sensor values. These estimates are compared to the measured values to assess instrument channel performance and to quantify the calibration status. Regardless of the underlying algorithm, all OLM systems construct models that calculate the parameter estimates. In this sense, the term model describes the empirical (or in some cases physical) relationships between signals that have been grouped together to perform signal validation. Several modeling techniques have been found suitable for OLM. The diversity of OLM technologies and their inherent assumptions makes OLM a complex topic. Using OLM to extend the required calibration interval has been investigated since the mid-90s; however, U.S. nuclear plants have not requested license amendments. This is most likely because the return on investment has not been proven; however, an OLM system has been successfully implemented on Sizewell B in Great Britain. In that case, sensor calibrations are on the critical path during a refueling outage and OLM has reduced the critical path by several days, resulting in a favorable return on investment.

The NRC acceptance of (OLM) systems for calibration extension is contingent on the system meeting 14 requirements outlined in the 1998 Safety Evaluation Report [NRC 2000]. Several commercial products are currently available and have been implemented on nuclear power plants for instrumentation and equipment monitoring but have not been utilized for extending calibration intervals. To extend the calibration interval, a plant must have a license amendment to change the technical specification. This report provides an overview of the three volume NUREG/CR-6895 series "Technical Review of

On-line Monitoring Techniques for Performance Assessment" for evaluating OLM systems for calibration extension.

2. Regulatory Basis

Each parameter covered by the Technical Specification has specific calibration/surveillance requirements that are performed at various frequencies. These requirements cannot be modified without approval from the NRC. Thus, when a plant implements an OLM system and wishes to extend the calibration interval for those channels included in an OLM system, they must first request a license amendment to change the Technical Specifications.

This extension of surveillance frequencies for specific plant instrumentation is based on the principle that evaluating the performance on a more frequent basis and comparing the results against pre-established acceptance criteria provides the same, if not better, confidence of operability than performing invasive checking and testing once every 18 months. However, the question "whether the frequent performance evaluation (OLM) is truly equivalent to the manual calibration", remains.

In an EPRI report, the results of a study conducted by EPRI and the Analysis and Measurement Services Corporation compared On-line Monitoring (OLM) and manual calibration methodologies for pressure, level, and flow transmitters installed at the Sizewell B nuclear power plant in Great Britain [EPRI 2006, Vols. I and II]. Many of the results of manual calibrations and OLM methodologies agreed well or were conservative (those in which OLM identified a sensor as bad while the manual calibration showed that it was within the acceptance range.) However, for 12 of the 175 cases, the OLM determined the sensor was within calibrations while manual calibrations identified the transmitters as out of calibration. The disagreement in the manual calibration and OLM results illustrates that a discrepancy can exist between manual calibrations and OLM. Each of the discrepancies between the two techniques' results is discussed in the EPRI report

It should not be a surprise that the two techniques gave conflicting results, for they were conducted at different operating conditions. Which method is better? That is a debatable issue. Some may say the OLM results are better since they were performed under normal operating conditions; however, others may argue that the manual calibration results are better because they are directly traceable to a standard. Actually, both methods have their advantages and disadvantages which have been pointed out in many published reports and in the NUREG/CR 6895 series. Ultimately, the utility and the NRC must weigh all of these issues and deicide if OLM is acceptable for calibration extension.

3. Relevant Guidance

An abundance of OLM research has been conducted and published by national laboratories, universities, utilities, and private companies. The Electric Power Research Institute (EPRI) has been very involved in OLM implementation and published several reports on the topic. The most notable EPRI report is TR-104965-R1, which is a revised version of the original TR-104965: the report which prompted the NRC's safety evaluation of OLM [EPRI 2000]. In the revised TR-104965, a description of the NRC's review and approval of OLM is included, along with a summary of EPRI's technical developments in the area of OLM. The NRC Safety Evaluation Report found OLM to have four inherent deficiencies:

> (*1) It is not capable of monitoring instrument performance for its full range including Trip Set Point (TSP),*
> *(2)It does not have accurate reference, but compares the measured value to a calculated reference (the process parameter reference) that itself is less accurate compared to simulated input used in the traditional calibration process,*
> *(3) It does not provide accuracy traceable to standards, and*
> *(4) It does not allow frequent physical inspection of the instrument or allow technicians to observe instrument anomalies.*

More recent EPRI reports exist that also provide valuable OLM information. EPRI published a three-volume series, "On-Line Monitoring of Instrument Channel Performance" which summarizes EPRI's OLM projects addresses how OLM systems can meet regulatory requirements [EPRI 2006, 2007]. Only the revised EPRI TR-104965 was reviewed by the NRC.

The NRC has also sponsored its own OLM research projects. One of the first research projects was a three-year comprehensive study to determine the validity of OLM. The study involved both laboratory and in-plant validation tests. The results of this study are contained in several NUREG/CR documents. The first document, NUREG/CR-5903, "Validation of Smart Sensor Technologies for Instrument Calibration Reduction in Power Plants" [NUREG/CR-5903, 1993], outlines the study's goals and provides a full description of the data acquisition system used in the study. The second document in the series, NUREG/CR-6343, "On –Line Testing of Calibration of Process Instrumentation Channels in Nuclear Power Plants" [NUREG/CR-6343, 1995], summarizes the study results which support the feasibility of on-line monitoring for assessing an instrument's calibration while the plant is operating.

OLM has not been used for calibration extension in the US, but has been approved in Great Britain and fielded at Sizewell B Nuclear Power Plant. British Energy Group and EPRI have published the application details, results, and lessons learned in a three volume set entitled "Plant Application of On-Line Monitoring for Calibration Interval Extension of Safety-Related Instruments" [EPRI 2006, 2007].

B. OLM Guidelines and Recommendations

1. Introduction

In accordance with 10-CFR 50, on-line monitoring systems for calibration extension "must be designed, fabricated, installed, and tested to quality standards commensurate with the importance of the safety functions to be performed." Before the NRC can accept a system for calibration extension, it must be demonstrated that the system in question meets all quality standards and requirements. This section is intended to help facilitate an NRC review of an OLM system for calibration extension. It describes some basic OLM concepts that relate to the safety and proper-use of any OLM system under consideration for implementation in a nuclear power plant.

2. Topics to be Reviewed

The topics to be reviewed reflects OLM topics and issues which were either poorly understood, had conflicting information in the literature, or were not yet explained but critical for the implementation of an OLM system. The applicant/licensee need not develop a separate document for each of the topics identified below; however, project documentation should encompass, or in some way address, each of these topics.

2.1 OLM Calibration Schedule

Current OLM techniques propose to relax the frequency of instrument calibrations required by the U.S. nuclear power plant Technical Specifications (TS) so that sensors would be calibrated based on their calibration condition, rather than simply calibrating every sensor at each outage. To prevent common mode failure and retain the standard traceability, OLM methods would still require at least one sensor from each redundant group be calibrated at each scheduled fuel outage. For *n* redundant sensors, all sensors will be calibrated at least once every *n* outages. Regardless of the number of redundant sensors in a group, a sensor cannot go more than eight years without being manually calibrated. If an instrument is found to exceed the drift limits it must be calibrated, regardless of when it is scheduled for calibration; therefore, depending on the performance of the monitored channels, anywhere from one to all of the redundant channels may be manually calibrated each fuel cycle. A clear scheduling method and proper documentation must be in place for an OLM system to be successful.

2.2 Non-Continuous Monitoring

Originally, EPRI assumed that OLM would be performed continuously; however, several members of the EPRI user's group have shifted to a periodic procedure. The SER [NRC Project no. 669, 2000] stated that quarterly monitoring is acceptable, so it is probable that some plants applying for a license amendment will wish to perform OLM on a quarterly basis. The only potential issue that arises when not applying OLM continuously is that an additional margin must be subtracted from the drift limits *(ADVOLM* and *MAVD)* equal to the amount an instrument may be expected to drift before the next OLM calibration assessment. Care must be taken to make sure plants have accounted for this margin, and that they understand that they can not seamlessly switch from continuous to quarterly surveillance without recalculating the *ADVOLM* and *MAVD*.

2.3 Model Development

The effort required for model development is contingent upon the complexity of both the OLM model and the process being monitored. Many factors must be considered during model development. The general process of model development is described in Chapter 4 of NUREG/CR-6895 Volume 1. Many common pitfalls that must be avoided during the model development process are illustrated in the limiting case studies found in NUREG/CR-6895 Volume 3. Some of these pitfalls include using too few or too many memory vectors (when using non-parametric models), choosing incorrect user-defined parameters (such as kernel bandwidths or weighting factors), using bad training data, or using an inappropriate model architecture. In most cases, the model development process is a non-linear optimization process and poor initial model performance may be unavoidable. An iterative improvement process may be necessary to produce a model with acceptable performance. This fact makes it necessary to have a high-quality model testing procedure so that a poorly developed model can be easily identified and corrected. Utilities should have a well documented model development process, complete with troubleshooting procedures.

2.4 Model Testing

Model testing is an imperative component of any OLM development methodology. Chapters 1 and 2 of NUREG/CR-6895 Volume 3 describe some common performance metrics that can be used during model testing and validation. These metrics can be used to identify problems with the model development process or test data. Additionally, both correlation analyses and reliability assessment modules have been shown to be valuable testing tools. During model testing and operation, the query data must still be encompassed by the training region. A correlation analysis can also be used to determine if the signals have a poor signal to noise ratio, which will degrade model performance.

A utility should have a well-documented model testing and validation procedures. These procedures should quantify acceptable ranges for the model performance metrics, correlation analyses, and also state what actions will be taken if these limits not met.

2.5 OLM Drift Limits and Setpoint Issues

Utility application of OLM has been focused on using it as a method to verify that no channel's performance is outside a prescribed deviation limit. Its application is not intended to affect either the trip setpoint or the deviation limit. In fact, all guidance given by utility working groups including EPRI's "On-Line Monitoring of Instrument Channel Performance, Volume 3: Applications to Nuclear Power Plant Technical Specification Instrumentation, [EPRI 2004c] focus on keeping the on-line monitoring acceptance criteria established in such a manner that setpoint calculations are not modified, and trip setpoints and allowable values remain unchanged. This is done by applying OLM only in cases in which the predictive uncertainty is less than the channel drift allowance. Requirement 6 in the SER [NRC Project no. 669, 2000] echoes that policy and requires

"… drift in the sensor transmitter or any part of an instrument channel that is common to the instrument channel and the on-line monitoring loop is less than or equal to the value used in the setpoint calculations for that instrument channel."

This requirement can only be met through the calculation of the uncertainty of the prediction with a high confidence (level of 95%/95%). Section 1.3.2 of NUREG/CR-8695 Vol.1 gives a discussion of the relationship of OLM to setpoint calculations. During that discussion the OLM errors were assumed to be random. More recent research shows this assumption probably will not hold when the sensor is drifting; therefore, this section will discuss how the OLM error should be considered.

The Instrumentation, Systems, and Automation Society (ISA) standard 67.04.01-2000, "Setpoints for Nuclear Safety-Related Instrumentation" [ISA 67.04.01-2000] provides a basis for establishing setpoints and ISA-RP67.04.02-2000, "Methodologies for the Determination of Setpoints for Nuclear Safety-Related Instrumentation" [ISA-RP67.04.02-2000] provides guidelines and examples for implementing ISA 67.04.01-2000. The Nuclear Regulatory Commission (NRC) Regulatory Guide 1.105 [NRC 1999] endorses Part I of ISA-S67.04-1994 with several clarifications as detailed in Regulatory Guide 1.105 and to Regulatory Information Summary (RIS) 06-017.

OLM tracks what is commonly referred to as sensor drift. Depending on the OLM implementation, the calculated residual may be used to estimate the channel drift and one must determine if it is a random error or is considered to be a bias. In either case one should make sure the type of error is correctly considered in the setpoint analysis when the total channel uncertainty was calculated.

For some of the channels, such as some pressure transducers, the random process noise is larger than the drift allowance and the residuals are filtered to remove random error components to determine the drift. In these cases the residual may be considered to be a bias. If the sum of the residual magnitude and uncertainty is being compared against the drift allowance used in the calculation of the total channel uncertainty in the setpoint analysis, then the drift allowance needs to have been treated as a bias in that calculation. It is common for the residual to be filtered to remove instrument noise in order to use a confidence interval rather than the larger prediction interval. The relationship between confidence intervals and prediction intervals is discussed in more detail in section 6.6 of NUREG/CR-6895 Volume 2.

Figure 1 (Figure 6-23 of NUREG/CR-6895 Volume 2) shows the relationship between the predictive uncertainty and the drift limit. In this example the drift tolerance is assumed to be 1%. When the uncertainty bound (red confidence or prediction interval) crosses the drift limit, one can not be 95% confident that the sensor has not drifted beyond its expected limit.

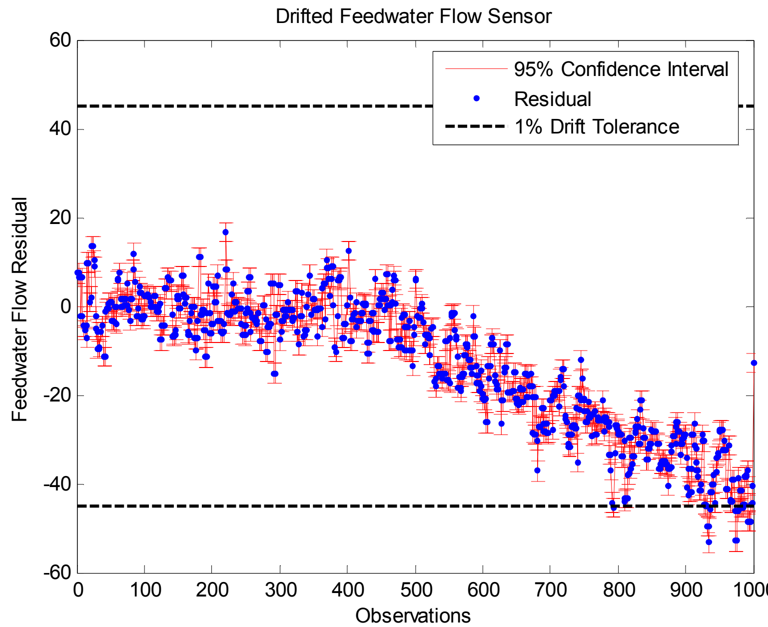

Figure 1. Filtered residual with 95% confidence interval of a drifted feedwater flow sensor

Several issues must be addressed when using this method of calibration monitoring. First, as just discussed, in this example the residual is filtered to remove the stochastic portion and one may need to consider this drift to be a bias.

The second issue arises from the monitoring interval length. The NRC SER [NRC Project no. 669, 2000] requires OLM be performed at least quarterly. If OLM is not performed continuously, then one must reduce the allowable drift tolerances by the amount that the sensor can be expected to drift in the next interval. For example, if an instrument has a 1% drift allowance for one 18 month fuel cycle, then it would be expected to drift as much as 0.22% (4/18) in one quarter; so the drift limit must be reduced by that amount to account for expected drifts during the next monitoring interval. Section 7.2.11 of NUREG/CR-6895 Volume 2 discussed this in more detail.

No utilities involved in the EPRI On-line Monitoring Working Group, EPRI Instrument Monitoring and Calibration (IMC) Users Group, or EPRI Fleet Wide Monitoring Interest Group (FWMIG) have contemplated changing the Trip Setpoint values. Rather, they have focused on implementing OLM as a technique to verify that the channel has not deviated into an unsafe range and thus does not need to be manually calibrated. They have also focused on the drift component of the channel uncertainties as required by the SER.

On-line monitoring evaluates the deviation of an instrument with reference to its process parameter estimate as determined by one of the predictive algorithms. A determination is then made as to the instrument channel performance. It is classified into one of the following categories:

1) The performance is acceptable,

2) The instrument must be scheduled for calibration, or
3) The instrument channel is inoperable.

OLM implementation requires procedures for classifying the instrument channel into one of these categories. Figure 2 (Figure 1-3 of NUREG/CR-6895 Volume 1) shows a drifting sensor with two example uncertainty intervals. If one doesn't have a 95% confidence that the instrument is within the **MAVD** (maximum acceptable value of deviation), then it must be reset. If one doesn't have a 95% confidence that the instrument is within the **ADVOLM** (allowable deviation value for on-line monitoring), then the instrument must be declared inoperable. Setting these limits is a licensee task, but is parallel to COT tests finding trips outside the tolerance and outside the deviation limit. When the trippoint is found to be outside the tolerance, the channel is reset so that there is 95% confidence it will not drift beyond the deviation limit before the next COT. When the trippoint is found outside the deviation limit, then the channel must be declared inoperable and corrective actions taken.

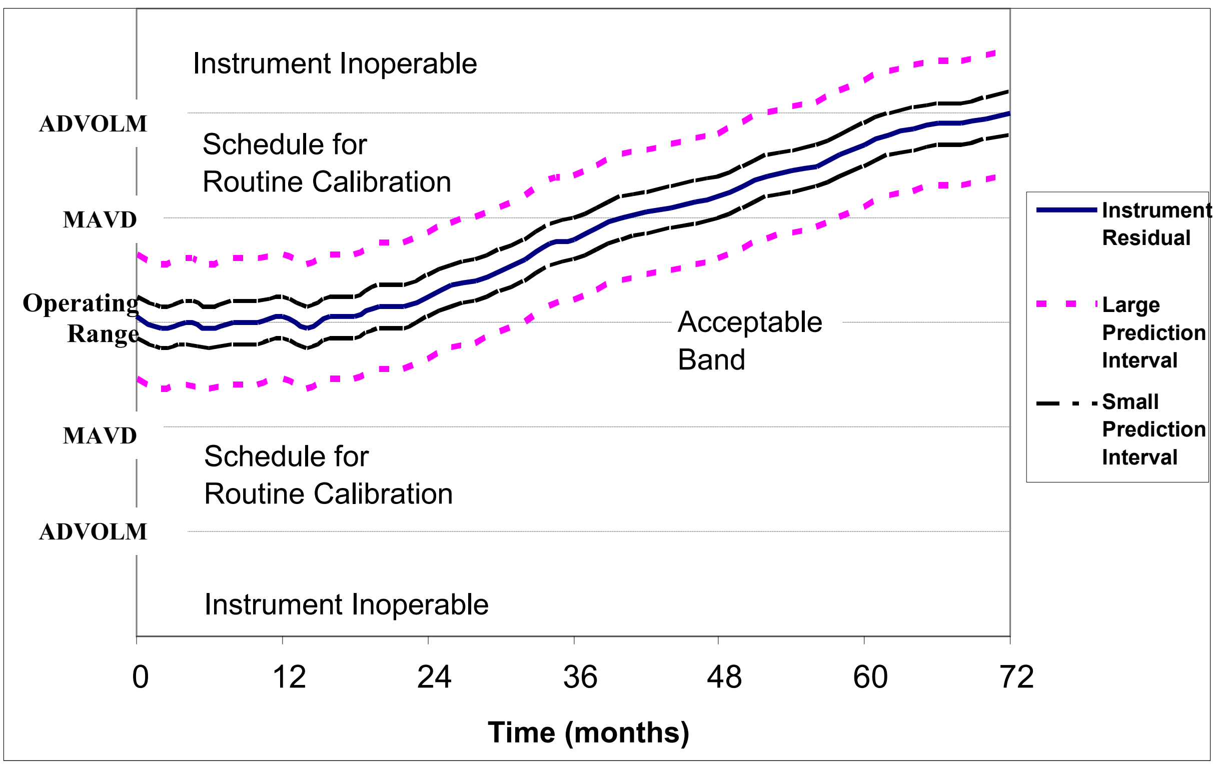

Figure 2. Sensor Status Deviation Zones

Figure 2 depicts continuous OLM, but can be implemented at predefined surveillance intervals. When implemented at intervals, the ADVOLM must be reduced to account for potential drift before the next OLM test. If continuous monitoring is used, this term is not needed and the ADVOLM can be considered to be the AV.

2.6 Uncertainty Intervals

Volume I only describes OLM uncertainty analyses in terms of prediction intervals (PI's), and does not mention confidence intervals (CI's) being used in more recent analyses. However, application has shown that noise in OLM sensors inflate the PI (which includes the noise variance term) to an amount that makes the residual exceed normal drift threshold values, even when no drift is present. Because of this, in many cases, PIs are unfeasible for use in quantifying OLM uncertainty. As such, Volume II examines methods of quantifying OLM uncertainty intervals and finds that the smaller CIs usually produce acceptable OLM uncertainties. Volume II provides the theoretical justification for using the CI. However, when models containing only a single group of redundant sensors are used, such as in ICMP or in a parity spaced based model, then the CI may no longer provide the baseline 95% coverage. Chapter 11 of Volume III gives further guidance as to how the proper uncertainty interval can be selected for small redundant models. Whichever uncertainty interval a plant chooses to use must have theoretical justification. The coverage metric (percent of the residual that is covered by the uncertainty bars) generally provides validating information of whether the interval is appropriate.

2.7 Model Detectability

Recent research has also shown that a model's auto and cross-sensitivity are of particular concern (also termed robustness and spillover, respectively). Auto-sensitivity (S_A) is a measure of an empirical model's ability to make correct sensor predictions when it's respective input sensor value is incorrect due to some sort of fault. Cross-sensitivity measures the effect a faulty sensor input (*i*) has on the predictions of sensor (*j*). At the time of Volume I's development, the impact of a model's sensitivity on the drift limits was not being considered. However, to be valid, it must be considered; because if a model's cross or auto-sensitivity is much larger than 0, then the model predictions will be affected by drift and may be unsuitable for OLM. Even with small (non-zero) sensitivity values, a model will still be unable to detect drift as accurately as it should, and the drift limits for the OLM system may need to be modified to reflect this fact. For instance, if a model has an auto-sensitivity of 0.2 and the drift limit is at 1%, the drift limit may need to be changed to 0.8% to account for the fact that the model will exhibit a 2% drift if any of the sensors in it have drifted. Researches at the University of Tennessee recently developed an Error Uncertainty Limit Monitoring (EULM) fault detectability program (which is discussed in Volume II) that provides a method for modifying the drift limits accordingly. The EULM program is certainly not the only viable method to account for detectability. There are numerous other ways that this can be done including using the CUMUM or Sequential Ratio Probability Test. The important requirement is that the method's assumptions should be listed and justified with actual data.

2.8 Fault Detection

Some OLM systems are not only being used to detect drifted sensors, but are also being used to detect other process anomalies or failures. The data collected for OLM contains valuable information about plant operations and process dynamics. Assertions regarding process or equipment reliability can often be made by analyzing this data. This type of fault detection can be considered an additional benefit of OLM systems that may be used to make them economically justifiable. Whether or not the system is used for this purpose is at the discretion of the nuclear plant. The use of OLM data for reliability analysis and process diagnostics should in no way influence the acceptance of an OLM system for calibration extension.

2.9 Model Retraining

Seasonal variations, equipment repair or replacement, and system operating changes can cause a change in the relationship between modeled variables. When the operating conditions change to that not found in the training set, the model is no longer representative of the current plant operating state and the model must be retrained with new data that is characteristic of the plant's current operating state. If the model is operating outside of its training range, no confidence can be given to the model's prediction. The analytical methods for uncertainty estimation will correctly increase the uncertainty estimates, but the Monte Carlo-based method will not be affected since its predictive uncertainty is a 95% worst case value estimated over the previously experienced operating range. The Monte Carlo method is permissible in situations in which the operating range is bounded and covered by the training data. However, some operational process needs to be in place so that users will be alerted to not trust the results and retrain the model if it is operating outside the training region.

2.10 Limiting Cases

Prior to implementing an OLM system for sensor calibration monitoring, the effects of various data faults, model development issues, and data conditioning methods should be understood. There may be data faults and abnormalities whose effect on model performance and applicability to an OLM system are currently unknown. NUREG/CR-6895 Volume III evaluates the modeling response to a set of various real-life scenarios in which the model development and execution assumptions that are outlined in Volumes I and II of NUREG/CR-6895 are violated. Examples of these scenarios include monitoring with query data outside the training region and model development with faulty training data. Also, the assumptions surrounding data de-noising, vector selection methods, different numbers of memory vectors, and distance measures must be understood and Volume III discusses each of these. Furthermore, special considerations may be needed for redundant sensor model architectures. The third volume presents the "lessons learned" from the experiences of developing and implementing OLM models under non-ideal circumstances and can provide some guidance as to how to handle or safeguard against these situations. In Volume III, an OLM model with an auto-associative kernel regression (AAKR) architecture was used to test these limiting cases. The AAKR model was chosen because it has an architecture similar to the commercially available non-parametric OLM models. The results presented in the report are not necessarily applicable to other modeling architectures such as neural networks, so their effects on alternate architectures should be investigated if alternate architectures are proposed. To meet this need, the report gives the method of performing tests to assess the effects of violating model assumptions and these tests can be adapted to other models. Although the study presented in Volume III is not an exhaustive review of the many issues in OLM system development, it provides a base set of considerations which must be accounted for and a method for testing these considerations with other model architectures.

2.11 Commercial Software Overview

There are many commercially available software packages available for OLM. The Analysis and Measurement Service Corporation (AMS) has developed OLM algorithms and software packages which use parity space methods to estimate the process parameter. AMS's OLM software is currently being used at Sizewell B in the United Kingdom [EPRI, 2006]. ExpertMicro Systems "SureSense Diagnostic Monitoring Studio" software offers both redundant sensor averaging methods and multivariable kernel regression methods that are menu selectable in order to optimize individual model performance. The "SureSense Diagnostic Monitoring Studio" is currently being used at the V.C. Summer Nuclear Stations [LAR 05-0677 2006]. Smart Singal Inc. has developed OLM software which uses an autoassocitive multivariate state estimation technique (AAMSET), which was developed at Argonne National Laboratory. In Europe, the Halden Reactor Project (HRP), which is an international research and development laboratory, has implemented several OLM algorithms, most notably autoassociative neural network (AANN) algorithms, and non-linear partial least squares in a package termed PEANO. Finally, researchers at the University of Tennessee have developed the Process and Equipment Monitoring (PEM) Toolbox [Hines, 2006], which is a MATLAB based set of tools that currently provide a generalized set of functions for use in process and equipment monitoring applications, specifically OLM [http://web.utk.edu/~dgarvey/pem/default.html]. The software packages mentioned in this paragraph are by no means the only products able to facilitate the acquisition and analysis of OLM data. These packages are simply the most visible in the U.S. nuclear industry at the time of this writing.

3. OLM Activities

3.1 Safety Analysis Activities

If properly developed and implemented, OLM may be a safer process than the current manual calibration scheme since calibration information is evaluated more often than current practice, and human errors and their potential impact on plant safety are reduced with the less frequent manual adjustment. To assure the increase in safety, any plant implementing OLM for calibration extension needs to perform a safety analysis. This safety analysis should demonstrate that OLM conforms to the plant's licensing basis. For calibration extension from 2 to 8 years, the main factors which could jeopardize safety are the accumulation of drift, and increase in the probability of dangerous failure affecting more than one safety channel. However, these safety risks are unlikely and can be considered small compared to the safety benefits from OLM. During the safety analysis, failure modes for the safety-related instrumentation should be evaluated for their impact on safety. The safety analysis should determine the probability of OLM creating a new or different kind of accident from any previously evaluated. IEC standard 62385, entitled "Nuclear Power Plants – Instrumentation and control important to safety – Methods for assessing the performance of safety system instrument channels", [IEC, 2007] can provide guidance on performing a safety analysis.

3.2 Software Verification and Validation Activities

All software used in the implementation must be verified and validated (V&V) and meet all quality requirements in accordance with NRC guidance and acceptable industry standards. Any currently available OLM software must be marketed as having successfully gone through a standardized V&V process. When filing a license amendment, the plant should be able to demonstrate that the necessary V&V activities have been performed to support the current version of the plant's OLM software. Chapter 6 of NUREG/CR-6895 Volume I discusses the V&V process. The V&V documentation for the SureSense Diagnostic Monitoring Studio, Version 1.4, MSET software is provided as an appendix in "On-Line Monitoring of Instrument Channel Performance Volume 3: Applications to Nuclear Power Plant Technical Specification Instrumentation" [EPRI 2004c]. Additional guidance on the V&V process is found in the IEEE standard, "Standard Criteria for Digital Computers in Safety Systems of Nuclear Power Generating Stations," NUREG/CRs "Software Reliability and Safety in Nuclear Reactor Protection Systems, "Design Factors for Safety-Critical Software", and "High Integrity Software for Nuclear Power Plants: Candidate Guidelines, Technical Basis and Research Needs [IEEE Std 7-4.3.2 1993, NUREG/CR-6101 1993, NUREG/CR-6294 1994, and NUREG/CR-6263 1995]

The software's OLM algorithm will most likely be propriety. However, the premise of this algorithm must still be understood and the uncertainty and detectability calculations theoretically sound. Further discussion of algorithm (or model) requirements can be found in Section 4 of Part B of this report.

3.3 Employee Training

For an OLM system to be successfully implemented, personnel from the plant's Engineering and IT departments will have to be properly trained. Both groups must have some understanding of the OLM system theory and functionality. The IT department, especially, must understand the computational and data system requirements. In particular, the process of collecting data and making it available often requires much technical support from the IT department. The appropriate utility personnel must also be aware of plant operating conditions. As mentioned in the model re-training section, process changes can result in the necessity for updating the OLM model. If there is a change in equipment or process, utility personnel involved in OLM process must be aware of these changes so that they can access the impact (if any) on the OLM system. Although most OLM software is automated, the OLM modeling process still requires human interaction. OLM predictions should never be trusted implicitly without first having a trained employee review and interpret the data. In filing a license amendment, the plant should be able to demonstrate the involved personnel have the necessary training and knowledge to correctly implement and support the OLM system.

3.4 OLM Implementation and Integration

Detailed procedures with realistic timelines must be in place for OLM to be successfully integrated. For example, many modeling techniques require that historical data be collected prior to implementation for model development and validation. For these models, the length of the data collection period must be long enough to acquire error free data representative of all future plant operating states. Many plants may have this data readily available; however, a plan must be in place for acquiring or accessing this data.

3.5 OLM Safeguards

Certain OLM systems may have additional safeguards which help prevent modeling errors. For example, a correlation and signal to noise ratio analysis can be used to assess the model's expected performance. Additionally, automated data clean-up utilities can be used to help identify bad data, such as outliers, interpolation errors, random data errors, missing data, or loss of significant figures, by either removing the bad data observations or by replacing it with the most probable data value using a data imputation algorithm. A reliability assessment module should be included the OLM system to evaluate the reliability of a model prediction and ensure the query data is covered by the trained operating range. However, perhaps the most important OLM safeguard is a human analyst. It is important that any nuclear plant using OLM be aware of the threat posed by bad data and have a designated person to visually inspect any data that will go into the development of their OLM system. Additionally, human expertise must be used to verify the OLM calibration results.

3.6 OLM Document Control

In accordance with 10 CFR Part 50 Appendix B Criteria VI, "Document Control," a system must be in place which "provides for the control of the issuance of documents, including changes thereto, that prescribe all activities affecting quality and provide for the maintenance of sufficient records to furnish evidence of activities affecting quality." This is especially true for OLM, where small changes in procedures or limits can have a dramatic impact on a transmitter's calibration status. Therefore, all OLM document must belong to a document control system, which ensures they pass through the correct personnel channels for review and approval. Nuclear plants will already have a document control system in place; however, it is vital that all OLM documents, records, and procedures are integrated into this system.

4. OLM Acceptance Criteria

In 1998, the Electric Power Research Institute (EPRI) submitted Topical Report (TR) 104965, *On-Line Monitoring of Instrument Channel Performance* for NRC review and approval. This report demonstrated a non-intrusive method for monitoring the performance of instrument channels and extending calibration intervals required by technical specifications (TS). A safety evaluation report (SER) was issued in 2000 [NRC Project no. 669] in which NRC staff concluded that the generic concept of on-line monitoring (OLM) for tracking instrument performance as discussed in the topical report is acceptable. However, they also listed 14 requirements that must be addressed by plant specific license amendments if the TS-required calibration frequency of safety-related instrumentation is to be relaxed. These 14 requirements can be considered the acceptance criteria for OLM and are discussed below. However, an additional requirement beyond the stated 14, is model acceptability. When the NRC originally reviewed OLM, they did not review or endorse any of the proposed modeling techniques. Thus, any OLM model or algorithm still needs regulatory approval. In Section 1.3.3 of NUREG/CG-6895 Volume 1, Summary of NRC Safety Evaluation Review, the 14 NRC SER requirements are provided in their entirety, along with a brief discussion of each. The second part of this section discusses model acceptability and criteria that can be used to evaluate individual OLM models.

4.1 NRC SER Requirements

Requirement 1

The submittal for implementation of the on-line monitoring technique shall confirm that the impact on plant safety of the deficiencies inherent in the on-line monitoring technique (inaccuracy in process parameter estimate, single-point monitoring, and untraceability of accuracy to standards), on plant safety will be insignificant, and that all uncertainties associated with the process parameter estimate have been quantitatively bounded and accounted for either in the on-line monitoring acceptance criteria or in the applicable setpoint and uncertainty calculations.

Much research has been conducted on quantifying the uncertainty associated with the process parameter estimate. Argonne National Laboratory (ANL), Expert Microsystems, SmartSignal, the University of Tennessee, and others have developed uncertainty analysis tools to quantify the uncertainty of the process parameter estimate. Each of the Volumes in NUREG/CG-6895 have devoted chapters describing methods to estimate OLM modeling uncertainty.

The single point monitoring issue concerns the probability that although the sensor appears to be in calibration at the operating point it may be out of calibration at another point in the process span. Since nuclear plants operate at nearly full power for the entire fuel cycle, resulting in few variations of the process parameter, this issue becomes very relevant in determining the ability of on-line monitoring to detect drift. EPRI conducted a large drift study using historical data from over 6,000 calibrations to look at the type of drift occurring. The results from this study proved that on-line monitoring was still valid even when the process is operating at a single point. However, to encompass the added uncertainty when the plant is operating with very little process change, a single-point monitoring penalty must be included with the other uncertainty terms in the drift allowance calculation. This approach will not influence the trip setpoint or the allowable value in the Technical Specifications. EPRI TR-104965-R1 presents a thorough discussion of the EPRI drift study and single point monitoring [EPRI 2000]. Additionally, some plants are choosing to include both start-up and shut down data in their OLM analyses to provide calibration information over most of the calibrated range of the transmitters being monitored, making the single-point monitoring penalty unnecessary [LAR 05-0677 2006].

Traceability to national standards is maintained in the OLM process as at least one transmitter from each redundant group requires manual calibration at each refueling outage.

Requirement 2

Unless the licensee can demonstrate otherwise, instrument channels monitoring processes that are always at the low or high end of an instrument's calibrated span during normal plant operation shall be excluded from the on-line monitoring program.

Transmitters that monitor unstable systems, such as auxiliary feedwater flow and safety injection, should be excluded from on-line monitoring. Also excluded are transmitters, such as containment pressure, that monitor systems that operate at the low end or high end of the operating range. EPRI Final Report 1007930 lists typical Technical Specification instrument channels that are both suitable and unsuitable for OLM [EPRI 2004c]. However, in some instances, the use of narrow range transmitters makes some channels that were originally considered unsuitable for OLM acceptable.

Transmitters instrument channels monitoring processes that are always at the low or high end of an instrument's calibrated span can still be monitored using OLM, but must be excluded from the calibration extension program unless it can demonstrate that the setpoints are sufficiently close to the operating point to obtain confidence in the results [EPRI 2006].

Requirement 3

The algorithm used for on-line monitoring shall be able to distinguish between the process variable drift (actual process going up or down) and the instrument drift and shall be able to compensate for uncertainties introduced by unstable process, sensor locations, non-simultaneous measurements, and noisy signals. If the implemented algorithm and its associated software cannot meet these requirements, administrative controls, including the guidelines in Section 3 of the technical report for avoiding a penalty for non-simultaneous measurement, could be implemented as an acceptable means to ensure that these requirements are met satisfactorily.

All of the algorithms currently being considered for on-line monitoring were designed with the intent that they distinguish between the process variable drift and the instrument drift. Kernel-based algorithms, such as AAMSET and AAKR, use the correlation of the instrument channels to differentiate the instrument drift from process changes. These algorithms are not susceptible to common mode drift because the correlation values for process drifts will be different than those for multiple instrument drifts.

The redundant algorithms (such as parity space or other averaging techniques) rely on the instrument's redundancy to distinguish between process changes and instrument drift. For the redundant techniques, multiple instrument channels are measuring the same value. Thus, the techniques assume that the a process drift will result in changes in more than one instrument channel, whereas an instrument drift will occur in a single channel without corresponding changes in the remaining redundant channels. While common mode drift may occur, the probability of this is slight and decreases further when there are more redundant channels.

Requirement 4

For instruments that were not included in the EPRI drift study, the value of the allowance or penalty to compensate for single-point monitoring must be determined by using the instrument's historical calibration data and by analyzing the instrument performance over its range for all modes of operation, including startup, shutdown, and plant trips. If the required data for such a determination is not available, an evaluation demonstrating that the instrument's relevant performance specifications are as good as or better than those of a similar instrument included in the EPRI drift study, will permit a licensee to use the generic penalties for single-point monitoring given in EPRI Technical Report 104965.

If OLM is using the transmitter's data throughout its calibrated range, then the single-point monitoring penalty is unnecessary. Some plants may include startup and shutdown data in their OLM system analysis. Although this data does not monitor the entire instrument range (especially near the trip setpoints), it is enough data to ensure that the instrument has not exhibited a span shift. A span shift occurs when a sensor may be in-calibration at its operating point, but its slope has shifted so that it is out of calibration at other operating points. However, many plants that implement OLM will not be monitoring instruments over an extended range and should be able to use the generic penalties for single-point monitoring given in EPRI TR-104965-R1 [EPRI 2000]. These penalties were conservatively calculated using data from over 6,000 calibrations. The EPRI drift study explains why these penalties are overly conservative for most applications. However, in order to use the generic penalty, the instrumentation must be fully represented by instrument manufacturer, model number, configuration, and ranges as those utilized in the EPRI drift study. If the plant chooses not to use the generic penalty, or the penalties do not apply, a formal design basis engineering calculation must be performed to calculate the penalty. EPRI TR-104965-R1 and EPRI Final Report 1007930 present the method for calculating a single-point monitoring allowance using plant specific data [EPRI 2000 and 2004c].

Requirement 5

Calculations for the acceptance criteria defining the proposed three zones of deviation ("acceptable," "needs calibration", and "inoperable") should be done in a manner consistent with the plant-specific safety-related instrumentation setpoint methodology so that using on-line monitoring technique to monitor instrument performance and extend its calibration interval will not invalidate the setpoint calculation assumptions and the safety analysis assumptions. If new or different uncertainties require the recalculation of instrument trip setpoints, it should be demonstrated that relevant safety analyses are unaffected. The licensee should have a documented methodology for calculating acceptance criteria that are compatible with the practice described in Regulatory Guide 1.105 and the methodology described in acceptable industry standards for TSP and uncertainty calculations.

The acceptance criteria for each instrument must be established through the application of formal design calculations. EPRI Final Report 1007930 provides the methodology for these drift allowance calculations [EPRI 2004c]. The only notable change to this methodology is that model detectability also needs to be accounted for in the drift allowance calculations. Still, using EPRIs calculation methods (with an added factor to account for drift) ensures that the Technical Specification trip setpoint and allowable value requirements do not require revision. In fact, the OLM allowance and uncertainties do not effect the setpoint calculations. The setpoint calculations do, however, effect the OLM allowances. The uncertainties unique to on-line monitoring, such as the process parameter estimate uncertainty and single point monitoring uncertainty, reduce only the on-line monitoring drift allowance. However, a concern could be that if a plant changes the method it uses to compute a setpoint, and the setpoint changes, the OLM allowances will also change. A procedure needs to be in place to make sure that these items are always consistent.

Requirement 6

For any algorithm used, the maximum acceptable value of deviation (MA VD) shall be such that accepting the deviation in the monitored value anywhere in the zone between PE and MA VD will provide high confidence (level of 95%/O/95%o) that drift in the sensor transmitter or any part of an instrument channel that is common to the instrument channel and the on-line monitoring loop is less than or equal to the value used in the setpoint calculations for that instrument channel.

EPRI Final Report 1007930 explains the basis for the calculations that ensure that MAVD provides a high confidence level [EPRI 2004c]. These calculations conform to all setpoint calculations standards. However, to truly meet this requirement, model detectability must also be taken into account. Detectability metrics measure the smallest fault that can be detected by an empirical model. The metrics quantify a model's ability to make correct sensor predictions when an input sensor's value is incorrect due to some sort of fault. Detectability can either be encompassed in the process parameter uncertainty estimate, or can be added to the drift limits as its own term. Researches at the University of Tennessee recently created an Error Uncertainty Limit Monitoring (EULM) fault detectability measure (which is discussed in Volume II and Volume III of NUREG/CR-6895) that is a method for modifying the drift limits taking into consideration prediction uncertainty and auto-sensitivity. The EULM program is certainly not the only viable method to account for detectability. There may be numerous ways that this can be done. An OLM system should use the calculation methodology described in EPRI Final Report 1007930, while also including a factor which accounts for model detectability. The drift limits should be reestablished each time operating conditions change, because this change will affect model detectability and uncertainty.

Requirement 7

The instrument shall meet all requirements of the above requirement 6 for the acceptable band or acceptable region.

The same basis for Requirement 6 applies to this region [LAR 05-0677 2006]. As previously mentioned, the plant must ensure that the methods used in calculating the setpoint and the OLM allowances are consistent.

Requirement 8

For any algorithm used, the maximum value of the channel deviation beyond which the instrument is declared "inoperable shall be listed in the technical specifications with a note indicating that this value is to be used for determining the channel operability only when the channel's performance is being monitored using an on-line monitoring technique. It could be called "allowable deviation value for on-line monitoring" (ADVOLM) or whatever name the licensee chooses. The ADVOLM shall be established by the instrument uncertainty analysis. The value of the ADVOLM shall be such to ensure:

> *(a) that when the deviation between the monitored value and its PE is less than or equal to the ADVOLM limit, the channel will meet the requirements of the current technical specifications, and the assumptions of the setpoint calculations and safety analyses are satisfied; and*
>
> *(b) that until the instrument channel is recalibrated (at most until the next refueling outage), actual drift in the sensor-transmitter or any part of an instrument channel that is common to the instrument channel and the on-line monitoring loop will be less than or equal to the value used in the setpoint calculations and other limits defined in 10 CFR 50.36 as applicable to the plant specific design for the monitored process variable are satisfied.*

This requirement hinges on the fact that plants are correctly calculating the OLM drift limits. By following the calculations described in EPRI Final Report 1007930 and also including a factor which accounts for model detectability, this requirement may be met. However, it is unnecessary to include the OLM drift limits in the Technical Specifications. EPRI Final Report 1007930 and License Amendment Request - LAR 05-0677 argue that the on-line monitoring acceptable criteria, including the MAVD and the ADVOLM, be included in a quarterly surveillance procedure and design basis documents, and not in the Technical Specifications [EPRI 2004c, LAR 05-0677 2006] . The references contend that OLM acceptance criteria can be included in quarterly surveillance procedures since the acceptable as-found settings and as-left settings for instrument calibrations are kept in the associated calibration documents, and not in the Technical Specifications. EPRI TR-104695-R1 outlines the prescribed quarterly surveillance tests that accompany the implementation of OLM [EPRI 2000]. Since the drift limits should be recalculated each time operating conditions change, including the actual values for them in the quarterly surveillance procedures and design basis documents is logical.

Requirement 9

Calculations defining alarm setpoint (if any), acceptable band, the band identifying the monitored instrument as needing to be calibrated earlier than its next scheduled *calibration, the maximum value of deviation beyond which the instrument is declared "inoperable, "and the criteria for determining the monitored channel to be an "outlier, "shall be performed to ensure that all safety analysis assumptions and assumptions of the associated setpoint calculation are satisfied and the calculated limits for the monitored process variables specified by, 10 CFR 50.36 are not violated.*

The regulation referred to in this requirement, 10-CFR50.36, defines the safety limits and limiting safety system settings that must be included in a plant's Technical Specifications. EPRI TR-104965-R1 helps to clarify the terminology used in this requirement, as it explains the possible operating points of an on-line monitoring channel. Again, formal design calculation should be used to determine the MAVD and ADVOLM values for each instrument. EPRI Final Report 1007930 provides a methodology for these calculations, which ensures the associated setpoint calculation allowances remain unchanged and that all assumptions of the associated setpoint calculation are satisfied and the calculated limits for the monitored process variables specified by 10 CFR 50.36 are not violated [EPRI 2004c]. However, the calculation methods described in EPRI Final Report 1007930 do not take into consideration model detectability. The calculations must be slightly modified to account for the OLM model's detectability. However, including a detectability factor in the drift limit calculations will still conform to all setpoint calculations standards and ensure that this requirement is met.

Requirement 10

The plant specific submittal shall confirm that the proposed on-line monitoring system will be consistent with the plant's licensing basis, and that there continues to be a coordinated defense in-depth against instrument failure.

In theory, OLM systems provide a continued defense-in-depth against instrument failure by its frequent evaluation of instrument performance. Unlike the traditional calibration schemes, which only evaluate instrument performance at each fuel outage, plants employing OLM technologies are required to perform calibration monitoring quarterly. However, these plants may elect to perform their calibration monitoring at even more frequent intervals. Furthermore, the continued calibration checks of the instrument channels (as OLM simply extends the frequency of manual calibration and does not eliminate them) provide added protection against instrument failure. However, a safety analysis should be performed to verify that the OLM System does not have a contributing failure mechanism applicable to plant instrumentation. With the proper isolation and independence (as discussed in Requirement 11) it is unlikely that any OLM system could introduce a new failure mechanism.

Requirement 11

Adequate isolation and independence, as required by Regulatory Guide 1. 75, GDC 21, GDC 22, IEEE Std. 279 or IEEE Std. 603, and IEEE Std. 384, shall be maintained between the on-line monitoring devices and Class 1E instruments being monitored.

It is anticipated that most OLM systems will have little trouble meeting this requirement. Both EPRI TR- 104695-R1 [EPRI 1993] and NUREG/CR-5903 [NUREG/CR-5903, 1993] discuss and diagram the OLM system's position relative to the rest of the instrument channel. These diagrams show that the OLM equipment boundary begins at the output of an isolator. In most cases, data obtained from the plant computer system is used for the on-line monitoring program. Since plant computers are already adequately isolated and OLM requires no additional hardware to be attached to the plant, this requirement is satisfied. This setup ensures that the isolation and independence between the on-line monitoring devices and class 1-E instruments meet all NRC Regulations.

Requirement 12
(a) QA requirements as delineated in 10 CFR Part 50, Appendix B, shall be applicable to all engineering and design activities related to on-line monitoring, including design and implementation of the on line system, calculations for determining process parameter estimates, all three zones of acceptance criteria (including the value of the ADVOLM), evaluation and trending of on-line monitoring results, activities (including drift assessments) for relaxing the current TS-required instrument calibration frequency from "once per refueling cycle" to "once per a maximum period of 8 years," and drift assessments for calculating the allowance or penalty required to compensate for single-point monitoring.
(b) The plant-specific QA requirements shall be applicable to the selected on-line monitoring methodology, its algorithm, and the associated software. In addition, software shall be verified and validated and meet all quality requirements in accordance with NRC guidance and acceptable industry standards.

All software modules used for acquisition and analysis of on-line monitoring data must be developed under a formal Quality Assurance (QA) program to include software Verification and Validation (V&V) and formal procedures for handling of the on-line monitoring data and the results. Plants should be able to meet part A of the requirement by following the applicable plant-specific quality assurance procedures when performing an engineering analysis in support of OLM implementation. In the analysis, the historical calibration data for plant pressure transmitters being included in the OLM calibration extension program should be used to verify that the transmitters have a history of stability.

The V&V methodologies must follow industry guidelines. When filing a license amendment, the plant should be able to demonstrate that the necessary V&V activities have been performed to support the current version of the plant's OLM software. Chapter 6 of NUREG/CR Volume I discusses the V&V process. The V&V documentation for the SureSense Diagnostic Monitoring Studio, Version 1.4, MSET software is provided as an appendix in "On-Line Monitoring of Instrument Channel Performance Volume 3: Applications to Nuclear Power Plant Technical Specification Instrumentation" [EPRI 2004c]. Additional guidance on the V&V process is found in the IEEE standard, "Standard Criteria for Digital Computers in Safety Systems of Nuclear Power Generating Stations," and the NUREG/CRs "Software Reliability and Safety in

Nuclear Reactor Protection Systems, and "Design Factors for Safety-Critical Software" [IEEE Std 7-4.3.2 1993, NUREG/CR-6101 1993, and NUREG/CR-6294 1994]

Requirement 13
All equipment (except software) used for collection, electronic transmission, and analysis of plant data for on-line monitoring purposes shall meet the requirements of 10 CFR Part 50, Appendix B, Criterion XII, "Control of Measuring and Test Equipment." Administrative procedures shall be in place to maintain configuration control of the online monitoring software and algorithm.

OLM equipment should include an isolated data collection system. The data for an OLM system should be acquired completely from existing channels without altering any instrument circuits. These instrument circuits already should meet all NRC regulations, including the control of measuring and test equipment. If an OLM system does require alteration of instrument circuits, it may be more difficult for the system to receive regulatory approval. In this case, it is recommended that the system's design is changed so that isolation of the instrument channel remains.

Requirement 14
Before declaring the on-line monitoring system operable for the first time, and just before each performance of the scheduled surveillance using an on-line monitoring technique, a full-features functional test, using simulated input signals of known and traceable accuracy, should be conducted to verify that the algorithm and its software perform all required functions within acceptable limits of accuracy. All applicable features shall be tested.

The software modules used to carry out these tests must be included in the verification and validation program. The procedure for an acceptance test and periodic test are included in EPRI Final Report 1007930 [EPRI 2004c]. Although this procedure is designed specifically for the SureSense software, it is still a very useful reference to plants using other on-line monitoring techniques. This report also discusses the full-features functional test, and even describes its recommended input. The results of all tests should be documented and kept in records so that they can be used as a baseline for comparison.

4.2 Model Acceptability

In their safety evaluation report, the NRC did not review or endorse either of the two algorithms addressed in the topical report, but instead, left the choice of algorithm up to the utility. However, during a license review, the technical details of each particular technique must be understood in order to determine if the technique meets the specified functional requirements. A licensee must have a complete description and justification for any model or algorithm proposed for OLM.

The NRC must have acceptance criteria for each OLM model being put forward for calibration extension. There is a proven theorem, called the "No Free Lunch" theorem

[Wolpert, 1997] that states that no empirical model is best for all situations. Therefore, it is not expected that any OLM model will consistently outperform another. Rather, each OLM model is expected to perform well given the data typical for the process its monitoring. This fact is why it is so important to have historical data available for acceptance testing from the actual location OLM will be applied. It is expected that the utility demonstrate the acceptability of their model using actual plant data. Generic data can also be used for the analysis, but it is important to include historical plant data.

To determine model acceptability, multiple datasets (both generic and plant-specific data) should be applied to the OLM model seeking regulatory approval (and possibly also several other common models to form a basis for comparison). Several parameters can be used to gauge model performance. The performance metrics described in Section 1.5 of Volume III of NUREG/CR-6895 may be useful in determining a model's aptitude in an OLM system. These metrics include accuracy, auto- and cross-sensitivity, and ICV and anomaly detectability. Accuracy measures the ability of a model to correctly and accurately predict sensor values and is normally presented as the mean squared error (MSE) between sensor predictions and the measured sensor values. The two sensitivity measures quantify a model's ability to make correct sensor predictions when an input sensor's value is incorrect due to some sort of fault. Finally, ICV and anomaly detectability quantify the smallest sensor calibration fault and anomaly that may be identified by an empirical model, respectively. An ideal model would be accurate, would have sensor predictions that are not appreciably affected by degraded inputs, and would be able to detect small sensor faults and anomalies. These performance metrics are all numeric values, facilitating easy comparison between models.

4.2.1 Process and Equipment Monitoring Toolbox

It is recommended that a model seeking regulatory approval be compared against several other model techniques. This comparison will show if the model is doing a good job predicting the data at hand. If all models are unable to make accurate predictions for the given plant data, it is possible that the process sensors are not well suited to OLM and should not be included in the calibration monitoring system. The Process Equipment Monitoring (PEM) Toolbox is a valuable tool that can be used to perform this comparison. The PEM Toolbox is a set of MATLAB based tools, developed at the University of Tennessee [Hines, 2006] to support the development of process and equipment monitoring systems. The purpose of this toolbox is to provide the necessary functionality such that different empirical modeling and uncertainty estimation methods may be investigated and compared. In addition, the design of these tools have centered about "ease of use", which allows for user's to gain access to complex modeling and analysis methods without detailed training.

The current architecture of the PEM Toolbox is organized into six function categories. The first category allows for data to be acquired from multiple sources and conditioned to assure data quality. The next category includes tools to aid in model development including variable grouping and multivariate model optimization. Once a model is developed, functions for parameter prediction and performance analysis may be used for several model types: autoassociative kernel regression which is similar to Expert

Microsystem's Expert State Estimation Engine (ESEE), MSET developed at Argonne National Laboratory [Singer et al. 1996] and used in SmartSignal Inc.'s eCM™ system, and the Autoassociative Neural Network (AANN) used in Halden Reactor Project's PEANO system [Fantoni 2005]. The final two function categories provide methods for uncertainty estimation and fault detection.

The PEM toolbox is available free of charge to the NRC. It can be used to evaluate or compare OLM models. Below is a short checklist of steps needed to test an OLM model. The first steps pertain to checking the data, and the next steps relate specifically to the model. The list provides the MATLAB codes found in the PEM toolbox needed to perform each step. Detailed help files are also included with the PEM toolbox that elaborate on each of these functions or tests.

4.2.2 Data Testing

- **Correlation Analysis**
  A correlation coefficient is a number between -1 and 1 which measures the degree to which two variables are linearly related. If there is a perfect linear relationship with a positive slope between the two variables, the correlation coefficient is +1. If the slope between the two variables is negative, the correlation coefficient is -1. A correlation coefficient of 0 signifies that there is no linear relationship between the variables.

  Comparing the correlation coefficients of the training and test data sets is an important step, as it gives valuable information as to if the operating state found in the training set is similar to that of the test set. It has been proven that nonlinear models do not have the ability to extrapolate beyond their training region with confidence. Linear models will extrapolate linearly and may be valid if the relationships between variables are strictly linear (such as in some redundant sensor sets). When plant operating conditions change, a non-linear model using training data from a different operating mode is no longer effective for predicting the current operating state of the plant. Chapter 5 of NUREG/CR-6895 Volume III discusses this in greater detail. Changes in the correlation coefficients between variables in the training and test sets can indicate that a model developed with data from the training set is not valid for the test data.

  Checking that the signals within each model's data set are well correlated is also an important step. If the sensors within a dataset are not correlated, then the variables cannot be modeled with certainty. This should show up in the uncertainty analysis, but low correlations should prompt additional oversight. As a thumb rule, two sensors whose correlation coefficient magnitude is larger than 0.7 are strong predictors of each other, if the correlation magnitude is above 0.3 there is some predictive information, and sensors with correlation magnitudes less than 0.3 have little use as predictors. The sign of the correlation coefficient is not important when determining the variable's usefulness for prediction.

Sensor correlation coefficients can also be an indicator of poor model training when at least some *a priori* knowledge of the sensor interactions is available. If sensors in a group were known to previously have strong correlations, low correlation coefficients in new data from the same group of sensors can be an indicator of errors in the data, such as outliers, drifts, or stuck data. Chapter 4 of NUREG/CR-6895 Volume III addresses faulty data and better explains how the correlation coefficient can be used to identify the faults.

- **Signal to Noise Ratio**
  Another important issue of data quality is the level of noise present in each sensor. This noise can include process noise, measurement noise, and electronic noise. Process noise is the natural perturbation of a parameter about its true value. This type of noise is particularly evident in flow and level sensors which have natural fluctuations due to "waves" about the intended value. Measurement noise refers to the noise inherent in the sensor. Electronic noise is the noise resulting from data transfer from the sensor to a central processor. These three noise contributors combine to cause random errors in the data. The general expectation is that as the noise level in a sensor set increases, model performance is degraded. If high noise levels are unavoidable, the effects on model performance can be reduced by denoising the data prior to model development and implementation. Chapter 6 of NUREG/CR-6895 Volume III examines the effects of noisy data, while Chapter 7 describes various de-noising methods.

- **Training data set coverage of the operating region**
  The test and validation datasets must come from the same operating state as the training data. If the training data do not cover the expected operation region, the model must be retrained, or in the case of most non-parametric models, the memory matrix must either be appended or replaced with new data that accurately represent the plant's current operating state. A correlation analysis is helpful in discovering if the training set is still valid. However, a reliability assessment module is more effective and should be used. The term "reliability assessment module" was introduced by the Halden Reactor group and has become a common term. It is a tool used to evaluate the reliability of a model prediction. A typical reliability metric would range from 0 to 1, with a metric of zero indicating that the model prediction is not reliable and a metric of 1 indicating that it is reliable. Reliability assessment should be performed in two steps. First, the assessment should determine whether the query vector is within the training data range. If the vector is not, the prediction is not reliably. However, if the query is within the range, the reliability is a measure of the similarity between the query vector and the training data.

- **Faulty training data**
  Training data containing outliers, drifted sensors, stuck sensors, and other types of bad data can seriously degrade model performance. Thus, careful review of any

acquired data that is going to be used in model development is necessary to assure its quality. Visual inspection of the data would identify each of the three types of faults investigated here. If data faults are identified in the training data set, some action must be taken before model development. If data anomalies such as outliers, interpolation errors, random data errors, missing data, or loss of significant figures are identified, the data should be processed to remove these faults. For this purpose, data clean-up utilities can be used to help remove these types of errors, by either removing bad data or replacing it with the most probable data value using some algorithm, such as linear interpolation. It is most common, however, to delete all bad data observations from the training data set.

4.2.3 Model Testing

- **Model Performance**
  Having a model that can detect drift is obviously the most important factor for OLM. Thus, a model's drift detection ability must be verified and quantified. To quantify this, an artificial drift must be inserted into each test data signal and then the data run through model and the OLM detectability determined.

- **Construct a model of known architecture (i.e. AAKR) with provided data to compare model performance**
  The use of a standard model, such as autoassociative kernel regression (AAKR), can be used to evaluate the ability of a data based model to predict sensor channel performance. Although no two models will produce the exact same predictions and uncertainties, it is still useful to see if they perform similarly for the given dataset.

All of the aforementioned tests, with the exception of the correlation analysis, are for models that are considered non-redundant. Non-redundant models are able to monitor sensors measuring correlated but not necessarily identical process parameters. In contrast, redundant sensors measure the same process variable at nearly the same location in the process. Models developed for redundant sensors, such as ERPI's Instrument and Calibration Monitoring Program (ICMP), require that all inputs come from truly redundant sensors. For instance, the simplest redundant model is just a direct average of the redundant sensor values. Even models that are classified as non-redundant, such as AAKR, may be used to only monitor a group of redundant sensors. However, these models are still called non-redundant simply because they are not limited to having only redundant sensor inputs. Empirical models designed for redundant sensors include simple averaging, the Instrumentation and Calibration Monitoring Program (ICMP) [EPRI 1993] and the parity space algorithm (PSA), also known as the generalized consistency check (GCC) [Upadhyaya et al. 1988]. Even though there are subtle differences in the model architectures, all perform a weighted average of the redundant sensors to estimate a single or multiple outputs.

The checklist above can be modified for redundant models. All of the steps in the Data category are still applicable. The only difference is that redundant models do not require that the dataset be divided into training, testing, and validation sets. However, it is still imperative to check for strong correlations in the data and a low signal to noise ratio. Redundant models are usually comprised of fewer sensors and generally rely on the fact that all of the sensor inputs are highly correlated. Under certain circumstances this high correlation is no longer present, causing many of the model assumption to no longer be met, and the model accuracy and performance to degrade. When sensor data is highly steady state, as is the case with most nuclear power data, the independent random noise may become the dominating factor. Because the data may be basically constant, the only fluctuation between the redundant sensors is due to the noise. In this case, the correlation coefficients between the redundant sensors are low (less than 0.5) because the independent noise is the prevalent component of each signal, causing each individual signal (or sensor) to be uncorrelated with the other signals. This low signal-to-noise ratio causes the model's performance to deteriorate (because the model's input do not contain much information about the underlying process), and the model's predictions become less reliable. Thus, it is very important to perform a correlation analysis and to check the signal to noise ratio of redundant modeling data. If the data is found to be very steady-state, increasing the sample size of the data used to develop the model may be necessary. Chapter 11 of the NUREG/CR-6895 Volume III focuses on the additional concerns that arise when redundant models are being used.

Another consideration when evaluating redundant models is that the method for quantifying uncertainty may be different from that for non-redundant models. As reported in Chapter 11 in NUREG/CR-6895 Volume III, research with the redundant sensor models has indicated that the confidence interval may not be an appropriate uncertainty measure, and alternatives must be considered. One such alternative is the prediction interval, which does not require the error to be smoothed and implements an additive relationship with the estimated noise variance, as opposed to the differential used by the confidence interval.

5. Conclusions

This report was written to provide supplemental guidance that can be used to assist in evaluating an OLM system. It serves as a supplement to the three-volume NUREG/CR-6895 series, "Technical Review of On-line Monitoring Techniques for Performance Assessment", and frequently cites where in this series critical information regarding OLM acceptance or implementation can be found. It also references several other OLM documents and describes how their content can be used to help understand the major issues involved with OLM system performance. Note that these other documents may have not been approved by the NRC. The latter sections examine the process of evaluating an OLM system proposed for calibration extensions. The 14 NRC requirements found in the SER of OLM are reviewed in more detail than in the NUREG/CR-6895 series.

C. References

EPRI (1993), TR-103436-V1, “Instrument Calibration and Monitoring Program, Volume 1: Basis for the Method,” EPRI, Palo Alto, CA.

EPRI (2000),"On-Line Monitoring of Instrument Channel Performance," Topical Report 104965-R1, EPRI, Palo Alto, CA.

EPRI (2003), "On-Line Monitoring Cost Benefit Guide", Final Report #1006777, EPRI, Palo Alto, CA.

EPRI (2004a), "On-Line Monitoring of Instrument Channel Performance, Volume 1: Guidelines for Model Development and Implementation". Final Report # 1003361, EPRI, Palo Alto, CA.

EPRI (2004b), "On-Line Monitoring of Instrument Channel Performance, Volume 2: Algorithm Descriptions, Model Examples, and Results", Final Report # 1003579, EPRI, Palo Alto, CA.

EPRI (2004c), "On-Line Monitoring of Instrument Channel Performance, Volume 3: Applications to Nuclear Power Plant Technical Specification Instrumentation", Final Report # 1007930, EPRI, Palo Alto, CA.

EPRI (2006), TR-1013486 "Plant Application of On-Line Monitoring for Calibration Interval Extension of Safety-Related Instruments: Volume 1", EPRI, Palo Alto, CA, and British Energy Group PLC, Suffolk, UK.

EPRI (2006), TR-1013486 "Plant Application of On-Line Monitoring for Calibration Interval Extension of Safety-Related Instruments: Volume 2", EPRI, Palo Alto, CA, and British Energy Group PLC, Suffolk, UK.

EPRI (2007), TR-1015173 "Plant Application of On-Line Monitoring for Calibration Interval Extension of Safety-Related Instruments: Volume 3", EPRI, Palo Alto, CA, and British Energy Group PLC, Suffolk, UK.

Fantoni, P. (2005), Experiences and Applications of PEANO for On-line Monitoring in Power Plants, *Progress in Nuclear Energy* for a special issue on *Lessons Learned from Computational Intelligence in Nuclear Applications*, "in press", Elsevier: 2005.

Hines, J.W., and D. Garvey (2006), "The Development of a Process and Equipment Monitoring (PEM) Toolbox and its Application to Sensor Calibration Monitoring", *Quality and Reliability Engineering International*, **22**, 1-13, 2006.

IAEA TWG, "On-line Monitoring for Improving Performance of Nuclear Power Plants; Part 1: Instrument Channel Monitoring", IAEA Nuclear Energy Series No. NP-T-1.1, 2008.

IEC 62385 (2007), "Nuclear power plants - Instrumentation and control important to safety - Methods for assessing the performance of safety system instrument channels", International Electrotechnical Commission, Geneva Switzerland, 2007.

Institute of Electrical and Electronics Engineers (1993), "Standard Criteria for Digital Computers in Safety Systems of Nuclear Power Generating Stations," IEEE Std 7-4.3.2, 1993.

ISA-67.04.01-2000, "Setpoints for Nuclear Safety-Related Instrumentation"

ISA-RP67.04.02-2000, "Methodologies for the Determination of Setpoints for Nuclear Safety-Related Instrumentation

License Amendment Request - LAR 05-0677 (2006) "On-Line Monitoring of Instrument Channel Performance," Virgil C. Summer Nuclear Station, Jenkinsville, South Carolina: February 2006.

NRC Project no. 669 (2000), "Safety evaluation by the office of nuclear reactor regulation: Application of on-line performance monitoring to extend calibration intervals of instrument channel calibrations required by the technical specifications – EPRI Topical Report (TR) 104965 *On-Line Monitoring of Instrument Channel Performance*," U.S. Nuclear Regulatory Commission: Washington, D.C.: July, 2000.

NRC Regulatory Guide 1.105 revision 3, 1999, "Setpoints for Safety-Related Instrumentation".

NUREG/CR-6101 (1993), Lawrence, J.D., "Software Reliability and Safety in Nuclear Reactor Protection Systems," (UCRL-ID-117524, Lawrence Livermore National Laboratory), USNRC, November 1993.

NUREG/CR-6294 (1994), Lawrence, J.D., and G.G. Preckshot, "Design Factors for Safety-Critical Software," USNRC, December 1994.

NUREG/CR-6263 (1995), Seth, S., et al., "High Integrity Software for Nuclear Power Plants: Candidate Guidelines, Technical Basis and Research Needs,", U.S. Nuclear Regulatory Commission, Washington, D.C., June 1995.

NUREG/CR-5903 (1993), Hashemian, H. M., "Validation of Smart Sensor Technologies for Instrument Calibration Reduction in Power Plants," U.S. Nuclear Regulatory Commission, Washington, D.C., January 1993.

NUREG/CR-6343 (1995), Hashemian, H. M., "On-Line Testing of Calibration of Process Instrumentation Channels in Nuclear Power Plants," Phase II Final Report," U.S. Nuclear

Regulatory Commission, Washington, D.C., November 1995.

NUREG/CR-6895, Vol. 1 (2006), Hines, J.W., and R. Seibert, "Technical Review of On-Line Monitoring Techniques for Performance Assessment, Volume 1: State-of-the-Art," U.S. Nuclear Regulatory Commission, Washington, D.C., 2006.

NUREG/CR-6895, Vol. 2 (2007), Hines, J.W.,D. Garvey, R. Seibert, and A. Usynin ., "Technical Review of On-Line Monitoring Techniques for Performance Assessment, Volume 2: Theoretical Issues," U.S. Nuclear Regulatory Commission, Washington, D.C., 2007.

NUREG/CR-6895, Vol. 3 (2008), Hines, J.W., J. Garvey, D. Garvey, and R. Seibert, "Technical Review of On-Line Monitoring Techniques for Performance Assessment, Volume 3: Limiting Case Studies," U.S. Nuclear Regulatory Commission, Washington, D.C., 2008.

Regulatory Guide 1.152 (1996), "Criteria for Digital Computers in Safety Systems of Nuclear Power Plants," Revision 1, U.S. Nuclear Regulatory Commission, Washington, D.C., January 1996.

Singer, R.M., K.C. Gross, J.P. Herzog, R.W. King, and S.W. Wegerich (1996), "Model Based Nuclear Power Plant Monitoring and Fault Detection: Theoretical Foundations," Proc. 9th Intl. Conf. on Intelligent Systems Applications to Power Systems, Seoul, Korea: 1996.

Wolpert, D. H., and W. G. Macready (1997), "No Free Lunch Theorems for Optimization," *IEEE Transactions on Evolutionary Computation*, 1(1), pp. 67-82.