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ON THE APPLICATION OF A RISK INFORMED GRADED APPROACH FOR ADVANCED CONDITION MONITORING PROGRAMS

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ACRONYMS

ACM	Advanced condition monitoring
ASME	American Society of Mechanical Engineers
ATR	Advanced Test Reactor
BOP	balance-of-plant
BPV	Boiler & Pressure Vessel
CDA	Cyber digital asset
CDF	Core damage frequency
CFR	Code of Federal Regulations
CM	Control measures
COS	Continued operational safety
DRAM	Digital reliability assessment methodology
EP	emergency preparedness
EPRI	Electric Power Research Institute
FAA	Federal Aviation Agency
FSAR	Final safety analysis report
IAEA	International Atomic Energy Agency
IEEE	Institute of Electrical and Electronics Engineers
IEC	International Electrotechnical Commission
IMP	Integrity management plan
ISI	Inservice inspection
IST	Inservice testing
MME	Maintenance management element
MSET	Multivariate State Estimation Technique
MSAD	Monitor Safety/Analyze Data
MPFF	Maintenance-preventable function failure
NBIS	National Bridge Inspection Standards
NEI	Nuclear Energy Institute
NPP	Nuclear power plant

NRC	Nuclear Regulatory Commission
RIGA	Risk-informed graded approach
OM	Operation and Maintenance of Nuclear Power Plants
PRA	Probabilistic risk assessment
PSO	Permanent slow order
PWR	Pressurized-water reactor
SFOBB	San Francisco Oakland Bay Bridge
SHM	Structural health monitoring
SSC	Structures, systems, and components
TARAM	Transport Airplane Risk Assessment Methodology
TSO	Temporary slow order
UFSAR	Updated final safety analysis report
VVUQ	Verification, validation, and uncertainty quantification

EXECUTIVE SUMMARY

This report was prepared for the U.S. Nuclear Regulatory Commission (NRC) to provide information, resources, success stories, and technical discussion towards development of risk informed graded approaches (RIGA) for advanced condition monitoring technologies (ACM). The ACM technologies considered in this work are advanced sensors and instrumentation, data analytics, machine learning and artificial intelligence, and physics-based models. The RIGA for ACM in this report entails identifying a regulatory review process proportional to the ACM program's risk level, incorporating both risk-informing and grading. The key findings and considerations from this effort are as follows.

- Existing nuclear related application of RIGA includes determining cybersecurity adequacy, identifying appropriate methods for fuel handling, and informing plant management procedures
- RIGA has been implemented successfully for regulated non-nuclear applications such as in aviation, railroad, and transportation
- A generic workflow for RIGA for ACM is developed in this report by examining common features of other approaches adopted within the nuclear and non-nuclear industry
- The RIGA for ACM workflow described in this report consists of six steps including: Scoping, Goal Setting, Detailed Design, Grade Determination, Grading Qualification, and Lifecycle Activities
- Key considerations in developing and implementing RIGA for ACM include impact on plant safety and reliability, system and component safety classification, ACM functionality and capability, and complexity of ACM technology

The ACM programs at nuclear power plants are expected to enhance the safety, reliability, and efficiency of plant operations and maintenance. Creating a RIGA review process for ACM programs will facilitate implementation of control and evaluation at appropriate and commensurate levels while maintaining the highest safety standards. There is significant interest in leveraging ACM to meet inservice inspection and inservice testing requirements at nuclear facilities. The insights presented in this report will support an objective and rigorous assessment of ACM, thereby enabling the safe and efficient adoption and application of ACM technologies.

1. INTRODUCTION

Advanced condition monitoring (ACM) programs represent a significant advancement in the management of nuclear power plant systems, structures, and components (SSCs). ACM programs support a proactive maintenance culture, where potential issues are identified and mitigated before they can escalate into significant problems. This not only extends the lifespan of critical components but also minimizes downtime and enhances the overall efficiency of plant operations. Utilizing advanced sensors, real-time data analytics, and decision structures, ACM programs provide detailed insights into the health and performance of critical systems. This facilitates a more precise assessment of potential operational risks and the prioritization of maintenance actions based on the condition of components, rather than relying on a fixed schedule or preventative maintenance practices. Although ACM technologies are being rapidly adopted into industrial applications, there is a lack of clear consensus on the definition or required technologies for ACM programs specific to nuclear power plant application. The variability in implementation and impact on plant processes necessitates a risk-informed graded approach (RIGA) for evaluating compliance with existing regulations and standards.

RIGA for ACM, in this report, involves determining the appropriate regulatory review process commensurate with the degree of risk introduced by the ACM program. A RIGA process involves two aspects, risk-informing and grading.

Risk-informing methodologies ensure comprehensive consideration during the implementation, validation, and deployment of ACM programs, while also assessing the level of risk associated with the technology. In essence, risk informing methods for ACM attempts to answer the risk triplet question, that is (1) what are the possible failures of the ACM technology (identification), (2) how likely are these failures (quantification), and (3) what are the potential negative effects of such failures (consequence)?

Grading further refines this by allocating the resources and effort, referred to as control^a measures (CMs), proportionate to the identified risk levels. A grading structure for an ACM could include distinct categories (e.g., A, B, C, D), where each category indicates a higher risk level. For each category, different control measures should be implemented, ensuring that the highest (and lowest) risk levels receive the appropriate level of regulatory oversight. This targeted strategy clarifies the level of effort required by both the ACM developer and regulator, and ensures that the appropriate review processes are in place that can account for ACM technology risks.

This report investigates risk-informing methods and grading approaches that currently exist within the nuclear and non-nuclear industries. The intent is to provide discussion on the development of a RIGA

^a *Control* referring to the control of a process or procedure. *Control* does not refer to instrumentation and control (I&C) systems.

framework for ACM programs in currently operating and future nuclear reactor facilities. An overview of the types of information that may be collected during the development of an ACM program and grading framework is also provided. As an example, four different potential grading frameworks for ACM programs are developed. A discussion on the considerations of each framework is also provided.

This report is structured as follows; Section 2 provides a brief overview of an ACM program; Section 3 reviews the use of RIGAs in nuclear and non-nuclear applications; Section 4 presents the considerations and information sources for developing a RIGA process with an ACM program; and Section 5 provides a comparison between different potential grading structures and their considerations.

2. ADVANCED CONDITION MONITORING

Condition monitoring is a familiar technology within nuclear power plants (NPPs), where plant operators monitor SSCs and determine if they are performing as expected and within technical specifications. Key examples include, but are not limited to, vibration analysis, ultrasonic testing, and lube/oil analysis. These processes typically involve significant human expertise and involvement in the interpretation of the state of the component. The motivation to introduce ACM is to further develop the capabilities of existing condition monitoring, introducing new insights and optimizations into plant processes.

What makes ACM unique from conventional condition monitoring is the type of information that can be derived from the underlying data as well as the ability to plan maintenance actions in a timelier manner. ACM in NPPs for active and passive components involves the use of complex models, decision structures, and data analytics to continuously assess the near real-time health and performance of SSCs. ACMs may employ digital twins, machine learning-based predictive models, or an array of sensor technologies to gather data on various parameters such as temperature, pressure, vibration, and material integrity. This data is then processed and analyzed to predict factors such as the remaining useful life of components and to detect early signs of degradation or potential failures. For active components like pumps, valves, and motors, ACM focuses on monitoring operational performance and identifying anomalies, indicating wear or malfunction. For passive components such as pipes, pressure vessels, and structural elements, ACM aims to detect material degradation, corrosion, and structural weaknesses. By monitoring for degradation, an ACM may provide decision information to plant operators on when and where maintenance actions need to be performed. ACM may also be used to support modifications to inservice testing and inspection (IST and ISI) frequency, where the frequency and extent of inspection activities are adjusted based on the condition and risk profile of components as opposed to periodic inspections. Previous work [1, 2] provides an investigation into how ACM and enabling technologies may be used to inform on IST and ISI activities. This optimizes maintenance efforts for organizational efficiency and also ensures enhanced compliance with regulatory requirements through the early onset detection of SSC degradations, ultimately reducing the number of unanticipated plant outages and transients.

An ACM program can vary significantly from system to system, containing different components, different objectives, different modeling methods, etc. There is currently no clear industry or regulatory consensus on what exactly an ACM program entails. However, at the most fundamental level, an ACM may have the following objectives:

1. **Sense:** An ACM program must be able to monitor the state of an SSC, directly through sensing instrumentation, or indirectly through derived information using sensing information.
2. **Model:** An ACM program must contain a mathematical model or expression that converts the sensing (or derived) information into more useful information, used either by an operator or another system. Models may vary in complexity; some may utilize advanced methods (e.g., machine learning) while others simple methods (e.g., alarming at setpoint).
3. **Respond:** The ACM must have an underlying purpose that relates to an NPP's lifecycle activities. The response of an ACM can vary depending on the desired outcome for a plant operator. A response can be as simple as alerting an operator to an anomaly or as complex as providing recommendations for scheduling maintenance activities for the SSC.

Due to the large variation in how ACM programs may be implemented, developing a “universal” regulatory review process may be difficult. A poor fitting “universal” process may place undue burden on simplistic ACM methods while also under regulating complex ACM methods. Therefore, a RIGA to ACM review is considered in this report, primarily to examine how to achieve the most appropriate oversight when provided a variety of ACM implementation methodologies.

An example of a condition monitoring program for nuclear reactors is provided based on the Advanced Test Reactor (ATR) at Idaho National Laboratory. The information is derived primarily from Refs. [3, 4].

The ATR is a pressurized water test reactor. As a test reactor, it operates at pressures and temperatures below large commercial nuclear power plants, where the main product for use from the reactor is neutrons rather than heat. The ATR relies on beryllium reflectors to concentrate neutrons at specific locations, enabling fuel and material testing (e.g., irradiation tests) [3]. The ATR's maximum power rating is 250 MW (thermal) with a maximum unperturbed thermal neutron flux of 1×10^{15} n/cm²s and a maximum fast neutron flux of 5×10^{14} n/cm²s [3]. The ATR is cooled by pressurized water (2.7 MPa/ 390 psig) that enters the reactor vessel bottom at an average temperature of 52°C (125°F), flows up outside cylinder tanks that support and contain the core, passes through concentric thermal shields into the open part of the vessel, and the flows down through the core at a temperature of 71°C (160°F) to a flow distribution tank below the core [3]. Primary coolant pumps situated outside the vessel circulates the water. At least two pumps operate along with one emergency cooling pump during reactor operation.

The fundamental principle for the ATR monitoring program is that intrinsic acoustic noise sources and extrinsic acoustically telemetered sensors will allow for the efficient real-time processing and non-intrusive characterization of a reactor under normal and transient conditions [3]. An advanced signal processing

algorithm is used to extract in-pile information, buried behind significant noise, to identify characteristics of the reactor process states. The measurement infrastructure for the monitoring program includes in-pile structural components, coolant, acoustic receivers, primary coolant pumps, a data acquisition system, and signal processing algorithms [3]. The monitored values include the periodic pulses originating from the rotating shaft of the five vane primary coolant pumps. The frequency harmonics generated by the pump vanes are nearly identical to signals that would be generated by acoustically telemetered sensors (e.g., thermoacoustic sensors) when inserted into the reactor core [3]. Piezoelectric accelerometers were installed on the reactor pressure vessel, flanges, and the hydraulic shuttle irradiation system in the ATR nozzle trench area to receive the acoustic signals. These acoustic signals are routed to National Instruments Compact Data Acquisition System 9205. Images of the piezoelectric sensors are shown in Figure 1.

The objective of the condition monitoring program is to establish acoustic baseline signatures for the ATR such that future trending analysis may be performed. However, while its application to condition monitoring and maintenance is recognized by the authors, the condition monitoring program for the ATR has not reached a level of maturity where maintenance recommendations can be made.

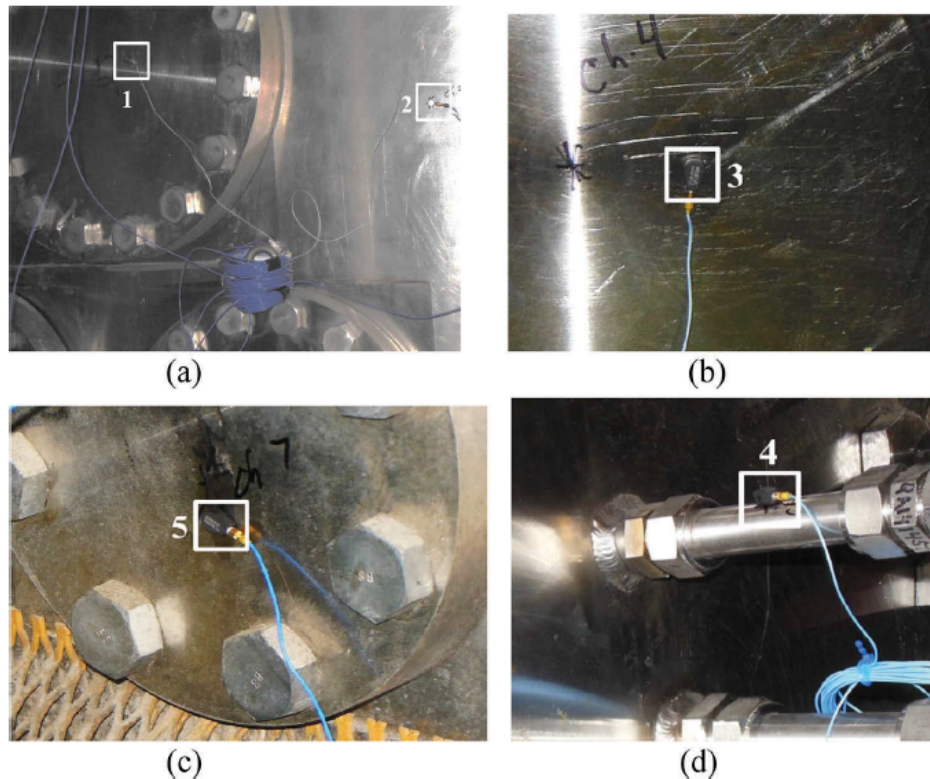


Figure 1. Piezoelectric accelerometers (acoustic receivers) installed in the nozzle trench area of the ATR. Receiver location 1 corresponds to the L2 flange, receiver location 2 corresponds to the pressure vessel, receiver location 3 corresponds to the L7 flange, receiver location 4 corresponds to the HSIS, and receiver location 5 corresponds to the C13 flange. Reproduced from Ref. [3].

3. STATE OF THE ART SURVEY ON THE ASSESSMENT OF ACM TECHNOLOGIES

RIGA is a relatively new concept and can be separated into two primary concepts: risk informing and grading.

Risk-informing represents a philosophy where risk insights, in combination with performance and functional SSC details, establish the requirements for the SSC [5]. This allows licensees and regulators to prioritize design and operational issues based on their significance to public health and safety. A “risk-informed” approach is intended to enhance (and not replace) an existing approach by: (a) allowing explicit consideration of a broader set of potential impacts to safety; (b) providing a logical means for prioritizing these impacts based on risk significance, operating experience, and/or engineering judgment; (c) facilitating consideration of a broader set of resources to optimize the safety impacts; (d) explicitly identifying and quantifying sources of uncertainty in the analysis; and (e) leading to better decision-making by providing a means to test the sensitivity of the results of key assumptions [5]. Risk-informed approaches strike a balance between purely deterministic and purely risk-based methods, producing outputs such as event frequency determination, SSC reliability data, and performance specifications [5].

Grading uses this risk information to determine the appropriate application of CMs based on the likelihood and potential consequences of component failures. In guidance from the International Atomic Energy Agency (IAEA) [6], they define a graded approach as “a process or method in which the stringency of the control measures and conditions to be applied is commensurate...with the likelihood and possible consequences of, and the level of risk associated with, a loss of control” [6]. In Ref. [7], the U.S. NRC further elaborates that those methods taken to control risk should be graded based on the potential consequences of failure—the higher the potential consequence, the more stringent the control actions should be. In the context of ACM, a graded approach can be understood as the actions, whether during development of the ACM or implemented as plant policy, taken to mitigate risks associated with the introduction of an ACM program to an SSC.

Together, RIGA is the process of identifying and quantifying the risks introduced by an ACM to an SSC followed by identifying the necessary controls to manage and mitigate those risks. In this section, a review of published nuclear and non-nuclear RIGA approaches is provided. The intent is to identify how risk information is utilized to guide grading, how grades are defined, and what qualitative or quantitative aspects are utilized when risk-informing or grading.

3.1 Survey in Nuclear Industries

RIGA has been used in various nuclear related applications, ranging from determining cyber security adequacy, identifying appropriate methods for fuel handling, and informing plant management procedures. The intent is to learn from these analogous scenarios how a RIGA process was implemented and the types of considerations needed when developing a RIGA for ACM.

In NEI 13-10 Ref. [8], the authors propose a risk-informed grading structure for cyber digital assets (CDA). This framework is intended to provide a systematic method for the evaluation and documentation of cyber security controls. Specifically, the framework provides steps for evaluating the qualitative risk impact of a CDA (through grades), the implementation of the relevant cyber security controls, and a method for documentation. NEI 13-10 identifies four different grades based on functionality of the CDA [8]: (a) emergency preparedness (EP), (b) balance-of-plant (BOP), (c) indirect, and (d) direct CDAs. Each functional grade is mutually exclusive; a system can only belong to one grade. For each functional grade, a minimum set of control measures (referred as security controls in [8]) are established that attempt to minimize consequences of a cyber compromise of the CDA. The grades include:

- The EP grade identifies CDAs that support plant performance, have an independent alternate means of performing functions, and do not perform/support other safety-related or important-to-safety functions.
- The BOP grade identifies CDAs that are important to safety functions in the BOP that can directly or indirectly affect reactivity, resulting in an unplanned shutdown or transient.
- The indirect grade identifies CDAs that do not perform safety-related functions and cannot have an adverse impact on safety-related functions including function, indication, and annunciation.
- The direct grade identifies all remaining CDAs (under NEI 08-09 [9]) not identified by the previous grades.

In this grading structure, determination of a CDA's grade is qualitative in nature and completed through a list of questions on the CDA's functionality and classification. Example questions include:

- Does CDA perform only an EP-related or EP support systems and equipment?
- Are one or more of the alternative means administrative, non-digital, or if digital is adequately independent?

NEI 13-10 [8] also provides a table of common control measures that can be applied for each grade. Evaluating whether a CDA is adequately protected against cyberattacks is also conducted qualitatively. For example, a BOP CDA may be considered adequately protected if all the following criteria are met:

- a. CDA is located within a protected or vital area or under security controls in NEI 08-09 [9],
- b. CDA and interconnected assets do not have wireless networking,

- c. CDA and interconnected assets are either air-gapped or isolated by a deterministic device,
- d. Use of portable media and mobile devices (on or around CDA) is controlled by NEI 08-09,
- e. Changes to CDA are evaluated and documented before implementation,
- f. CDA is periodically checked to ensure the equipment is capable of performing its function,
- g. Ongoing monitoring and assessment are performed to ensure the security posture of the CDA is maintained.

By using this process, a licensee can demonstrate that alternative controls and countermeasures are in place and sufficient to provide adequate protection of CDAs. This grading structure was used in Ref. [10] to reduce the evaluation effort required for security controls by 30% for all CDAs.

In Ref. [7], the authors discuss RIGA for decommissioning nuclear material handling facilities such as laboratories, research reactors, and small manufacturing facilities. The authors identify that smaller facilities that utilize lower quantities of radioactive materials may present different hazards and potential consequences than larger facilities and would therefore need a different graded approach in decommissioning. The graded structure presented is based on the nature, quantity, and extent of the radioactive material present at the facility. Each of the seven grades (i.e., 1 through 7) identifies a specific material handling scenario. Note in this grading structure, the grades do not reflect increasing or decreasing severity but rather the type and quantity of radioactive material on site. This is because the procedures will differ when presented with different quantities and types of radioactive material per site and thus do not scale with grades. The intent of the graded approach in this example is to achieve approximately the same level of risk across each group in a safe and cost-effective manner.

In Ref. [11], the authors discuss implementing RIGA to select institutional controls under the license termination rule for radioactive dose release. They identify two grades based on hazard level and likelihood of hazard occurrence: (a) sites below 1 mSv/yr (100 mrem/yr) dose requiring enforceable institutional controls and (b) sites above 1 mSv/yr (100 mrem/yr) dose requiring both enforceable and durable institutional controls. These grades are established based on 10 CFR 20.1403 [12]. Lastly, they identify that the graded approach has specific benefits, namely it clarifies to licensees when increasing levels of control are needed to mitigate site-specific risks.

In Ref. [6], the IAEA proposes the use of a graded structure for developing the requirements of an integrated plant management system. The premise being that the management system requirements should be developed commensurately with the potential risks associated with the facility or activities, or with the consequence of losing knowledge (e.g., records). The overall intent is to ensure resources are deployed efficiently and effectively, and that the appropriate controls are applied based on the significance to health

and safety. The Ref. [6] definition of grades specifically accounts for: (1) the complexity of a product or service, (2) the potential impacts to health, safety, security, environment, and organizational objectives, and (3) the consequence of a product failure. Several different methods for developing grades are presented in Ref. [6] including:

- **By Maturity** – The system is graded by the level of maturity/experience available in the product, service, or SSC. For instance, design maturity grades systems by the availability of an equivalent design which has proven efficacy. The assumption is that for mature designs, multiple developers will utilize the same design as opposed to developing a new design.
- **By Complexity** – The system is graded by the level of effort required to support or develop the system. For instance, design complexity grades systems by the difficulties to be encountered in the effective implementation of the process (e.g., material selection, stress analysis, etc.)

Determining which grade a system belongs to can be accomplished via SSC safety classification; where SSCs that share characteristics or functions are grouped together, for instance by technical considerations pertaining to safety function and safety significance. Alternatively, grade determination can be conducted through qualitative evaluation of the proposed activity.

For example, in Annex VI for Ref. [6], a graded approach to evaluating quality assurance and control activities in the procurement supply chain is presented. In this example, the equipment class and influencing factors are used to determine the degree of risk of procurement of the component and the necessary control actions to ensure successful procurement. To determine risk levels, two axes are used: equipment safety class and influence factors.

Equipment safety class is the safety classification of the equipment based on existing standards or regulatory guidance. For example, major engineered (class A), major electrical (class B), main static (class C), rotating (class D), static (class E), and standard/catalogue commodities (class F).

The influence factor considers the inherent risk of an activity as well as the major objectives and parameters of concern (e.g., industrial safety, design maturity, environmental risk, and commercial risk). An influence factor could include *Environmental Impact*; a score can be assigned based on the degree of impact from *No Significant Impact* (Score: 1), *Moderate Impact* (Score: 2), and *High Impact* (Score: 3). The summation of all influencing factor scores is then used for grading in combination with the equipment class.

Figure 2 shows how to use the two grading values to determine the appropriate risk level. For class D equipment with an influencing factor sum of 17, the risk level is 3.

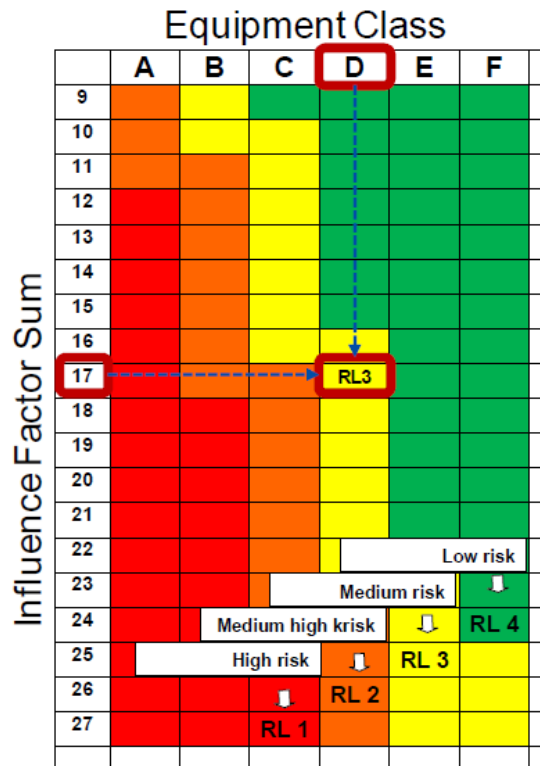


Figure 2. Risk Matrix to determine risk levels based on influence factor sum and equipment class.

For each risk level and at each stage of the procurement lifecycle (e.g., supplier qualification, fabrication, transportation, etc.) there are specific control measures that must be implemented. Figure 3, shows an example of the types of control measure to be implemented based on the identified risk levels.

Activity	Graded Controls	Risk Levels			
		1	2	3	4
Supplier Qualification The licensee should ensure the contractor has the required QA program implemented.	Supplier audited by licensee audit.	X	(X)		
	Supplier certified by third party registrar (e.g. ISO 9001).		X	X	
	Supplier's QA documentation accepted by licensee.	X	X	X	X

Figure 3. Example of an activity-risk table with graded controls based on risk levels. Derived from Ref. [6].

In this supply-chain example, compliance by the licensee is demonstrated when all control measures corresponding to the identified risk levels are implemented.

Aside from NRC guidance on developing RIGA methods, the U.S. Department of Energy also has a set of guidance related to a graded approach for non-power producing nuclear sites. In “Nuclear Facility Maintenance Management Program Guide for Use with DOE O 433.1B” [13], federal and contractor organizations are required to use a graded approach to ensure that the level of rigor for implementing maintenance management elements (MME) is based on their importance/significance and associated consequences. The document identifies seventeen relevant MMEs which are listed below:

1. Integration with Regulations and DOE Orders and Manuals (and their CRDs);
2. Maintenance Organization and Administration;
3. Master Equipment List;
4. Planning, Scheduling, and Coordination of Maintenance;
5. Types of Maintenance;
6. Maintenance Procedures;
7. Training and Qualification;
8. Configuration Management;
9. Procurement;
10. Maintenance Tool and Equipment Control;
11. Suspect and Counterfeit Items;
12. Maintenance History;
13. Aging Degradation and Technical Obsolescence;
14. Seasonal Facility Preservation;
15. Performance Measures;
16. Facility Condition Inspection;
17. Post Maintenance Testing.

Each MME includes separate implementation guidance, additional or supporting background, and example templates and checklists. Ref. [13] identify that a graded approach should be utilized for each MME to ensure that the level of analysis, documentation, and actions are commensurate with:

- a. The safety, safeguards, and security function provided;
- b. The magnitude of any hazard involved;
- c. The life-cycle stage of a facility;
- d. Programmatic mission of a facility;
- e. Particular characteristics of a facility;
- f. The relative importance of radiological and non-radiological hazards; and
- g. Any other relevant factor.

Note that while a graded approach is required, Ref. [13] does not provide explicit guidance on the methods to form a graded approach, instead identifying that a graded approach is a requirement. The section on predictive maintenance is reviewed to provide an idea of the content discussed.

Ref. [13] identifies that predictive maintenance may be used at nuclear facilities if they consist of measurements or tests that detect equipment or system conditions. Where results can be analyzed to determine what degree of maintenance is required and when it is needed, these activities should be less invasive, time-consuming, and costly than preventative or corrective maintenance. Ref. [13] identifies different predictive maintenance technologies, including but not limited to: bearing temperature monitoring, infrared thermography, acoustic testing, etc.

In many of the aforementioned approaches, probabilistic risk analysis (PRA) is the primary method to derive risk information. While PRA is useful, equipment data inadequacy may hinder the process. This may be true for novel technologies that would be used in ACM programs. An alternative to conventional risk analysis (e.g., PRA) for plant maintenance planning is the use of margin analysis. This method determines the available operating margin of an SSC, and the impact an ACM program may have. Rather than focusing on the likelihood of a given event (in probabilistic terms), margin analysis assesses how “far away” this event is from occurring by assessing how close an asset is to reaching an unacceptable level of performance or failing [14, 15]. Ref. [15] discusses the use of risk-informed asset management as an alternative to reliability quantification of SSCs. Note that *margin* is an analytical metric that is designed to quantify the health of an SSC. It is not a static condition but will change with time depending on the SSC condition. Determination of the margin is based on current or past operational experience and requires two data sources: an estimation of the actual health condition of the SSC and the limiting condition that must be avoided. Figure 4 provides a graphical representation of margin analysis.

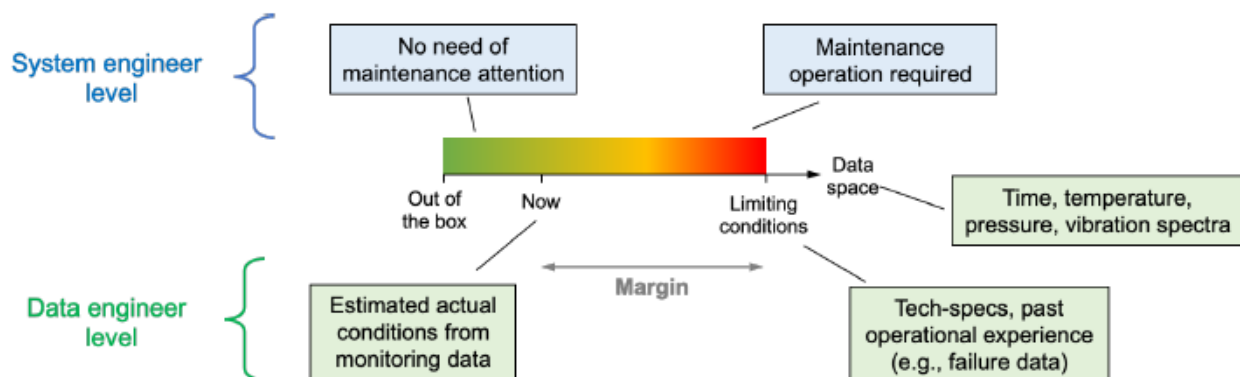


Figure 4. Graphical representation of margin based on actual asset monitoring data. From Ref. [15].

A margin value, M , for an asset is defined over the $[0,1]$ interval where $M = 1$ corresponds to a perfectly healthy asset (which requires little or no maintenance attention), while $M = 0$ corresponds to a faulty asset (which requires maintenance attention). This mindset shift on the concept of reliability (margin based rather than probability based) has the advantage that it provides a direct link between the asset health evaluation process and standard plant processes used to manage plant performance (e.g., plant maintenance operation and budgeting processes). The transformation also places the question into a form that is more familiar and readily understandable to plant system engineers and decision makers. As an example, when dealing with condition-based data (current and historical data), the margin may be defined as the distance between actual and past conditions (e.g., oil temperature, vibration spectrum) that lead to failure. However, note that margin quantification is heavily impacted by the availability of monitoring data over defined variables such as pressure, vibration, and time. In essence, margin analysis is still heavily data reliant, as is PRA, but may utilize a different set of data than PRA.

3.2 Survey in Non-Nuclear Industries

In this section, a survey on the application of RIGA and similar approaches in non-nuclear industries for ACM is presented. This report examines how aviation, civil structures, and hazardous material pipelines (e.g., crude oil) conducts risk informing or grading for condition monitoring. In these industries, RIGA for ACM does necessarily refer to a graded review process but can also refer to graded actions in response to a risk event (i.e., degradation). Furthermore, industries sometimes utilize different terms when referring to condition monitoring, risk-informed, and graded approach. At the bare minimum, an ACM analog in other industries should at least monitor the targeted system and inform an operator when a system is anomalous. A RIGA analog should at least use risk information to determine the type of activity that should be completed commensurate to degree of impact on operational goals (e.g., availability, reliability, etc.).

3.2.1 Use of RIGA in Aviation Structural Health Monitoring

Within the aerospace industry, manufacturers are promoting structural health monitoring (SHM) to reduce long-term maintenance costs while also increasing aircraft availability and weight savings. In essence, SHM in aircraft involves the use of advanced technologies (e.g., fiber optic sensors, acoustic emission sensors, etc.) and methods to continuously assess the integrity and performance of an aircraft's structure. This process aims to detect damage or degradation early, reducing downtime and permitting maintenance schedule optimization. While SHM technologies and configurations may vary, in practice, SHM systems use embedded real-time networks of integrated sensors to detect structural damage to reduce human error during inspection and flight operation [16]. In this sense, SHM is analogous to condition monitoring of NPP SSCs.

RIGA for SHM involves determining the types of maintenance actions that should be performed commensurate with the severity of the degradation. For example, the grades for SHM on general periodic aircraft maintenance procedures include (a) walkaround, (b) service checks, (c) line-maintenance (A-checks), (d) detailed line-maintenance (B-checks), (e) detailed maintenance and inspection (C-checks), and (f) heavy maintenance/overhaul (D-checks). The grades reflect an increasing level of effort on the inspection and activities performed. Activities up to B-checks can be accomplished overnight while C-checks and D-checks approximately require one week and one month respectively. C-checks and D-checks are ideally deployed only when specific degradation conditions are detected. In this context, RIGA for SHM is used to determine which checks should be performed. SHM may also be combined with risk analysis to demonstrate airworthiness with respect to continued operational safety (COS)^b.

For example, the Transport Airplane Risk Assessment Methodology (TARAM) is a Federal Aviation Administration (FAA) endorsed process to calculate risk associated with COS issues within the U.S. transport airplane fleet. The risk-analysis calculations from TARAM are used to make determinations of unsafe conditions in airplanes, and for the selection and implementation of corrective/maintenance actions. Similar to nuclear PRA, TARAM has steps for hazard identification, occurrence probability quantification, consequence analysis, and risk evaluation and mitigation. However, TARAM simplifies risk analysis through several key assumptions in its deployment. These simplified assumptions are not necessarily beneficial as in Ref. [17] they identify how these deficiencies limit the TARAM process in its capability at consistent and evidence-supported risk assessment. Deficiencies include:

- 1) Human reliability analysis is not conducted in the TARAM handbook. No human reliability data source is explicitly identified nor is a method for collection provided by the TARAM handbook [17],
- 2) No explicit guidance on the treatment of epistemic uncertainty including quantification [17],
- 3) Quantitative CCF analysis is not conducted in the TARAM analysis or used in COS decision-making. No CCF data source is explicitly identified in, nor is a method for collection provided by, the TARAM handbook [17],
- 4) TARAM's risk analysis involves examining causal chains. The construction of these chains is not based on 14 CFR 25.1309 fault tree analysis (or equivalent probabilistic analysis methods) [17].

TARAM analysis results are intended to support the Monitor Safety/Analyze Data (MSAD) FAA Order 8110.107B. The MSAD process provides a data-driven risk-based approach for safety assurance and safety

^b COS refers to the processes and procedures that ensure an aircraft remains in a safe and airworthy condition throughout its operational life.

risk management through an aviation product’s lifecycle. The risk results derived from MSAD are used for decision-support when making corrective and/or mitigative actions to address a hazard. For instance, following preliminary risk assessment, a decision is made regarding the type of immediate action that should be performed based on the qualitative interpretation of the degree of severity of an identified hazard. The types of qualitative interpretations include a) unsafe & urgent, where immediate corrective action is needed, b) potentially unsafe, where additional quantitative risk analysis is performed, c) potential aerospace system level safety risk management, and d) potential hazard related to cybersecurity. MSAD does not explicitly provide quantitative criteria for hazard urgency interpretation but identifies that an expert panel should be assembled to gauge urgency.

Operators intending to implement an SHM program may do so under exemption, 14 CFR Part 121 [18], but must show that the new process is sufficient via an alternate means of compliance [19]. Demonstration of SHM program (and RIGA-based maintenance) compliance is conducted through a validation exercise which provides quantifiable evidence that the SHM or maintenance methodology can achieve a satisfactory result. Typically, these validation exercises are completed on real-life validation assemblies which are full-scale models that contain realistic defects or other operational malfunctions which the SHM system is intended to monitor. The validation process involves conditions identical to day-to-day inspection environments and activities that would be performed on a typical aircraft. These tests are then assessed against industry standards to ensure compliance in both the monitoring and potential modification to maintenance activities. Some of the criteria to evaluate the SHM validation exercise are shown in Table 1.

Table 1. Example of SHM validation exercise criteria and measures [16].

Criteria	Description	Measure
Accuracy	Correct flaw locating/high probability of detection	Ratio between flaws detected over actual number of flaws
Calibrated	Low probability of false indication	Ratio between false detections over all detections
Versatility	Detect flaws in a variety of locations & under different circumstances and configurations	Number of recalibrations required for different circumstances
Portability	Ease of shipping and handling	Can be relocated to meet inspection demands

In summary, while RIGA SHM is a viable framework for the aviation industry, specific processes may not be transferable to the nuclear industry due to the high bar of demonstration. For example, while to-scale airplane validation assemblies are economically feasible, as they derive the same mass-manufactured equipment as a typical airplane, this may not be applicable for nuclear reactor ACM programs. U.S. nuclear

reactors typically have specialized components; validation on a single to-scale version may not provide sufficient evidence to generalize validation of the ACM across similar components.

3.2.2 Use of RIGA in Civil Engineering Structural Health Monitoring

Risk-informed decision making for inspection and maintenance activities are well-established in civil engineering (e.g., bridges). In 23 CFR Part 650, subpart C, “National Bridge Inspection Standards” (NBIS), identifies the proper safety inspection and evaluation of all highway bridges. Specifically, Part 650.311 involves bridge inspection using a risk-based method. The intent of risk-based methods is to determine the maximum inspection intervals without impact to bridge reliability, decided by a committee of experts (known as the Risk Assessment Panel). The overall process involves identifying deterioration modes that are used to classify probabilities and consequence levels, depending on the bridge considered. Condition data related to the bridge may be used to develop an evaluation procedure (i.e., vibration monitoring). The panel also develops a set of scoring criteria to assess risk for each bridge member in terms of probability and consequence on structural safety or serviceability loss due to inspection. An example of scoring can be found in Section 3.2.4.1. The risk-based method may extend routine inspection intervals to 12, 24, 48, or 72 months, depending on the condition of the bridge.

3.2.3 Use of RIGA in Pipeline Structural Health Monitoring

The Integrity Management Program (IMP) is a regulatory requirement under 49 CFR, Part 195.452 [20] and identifies the use of risk-based approaches to improve pipeline safety. The objectives of IMP are to perform integrity assessments of pipelines in locations of high consequences, improve operational management of pipeline integrity, increase public confidence in pipeline safety, and increase the governments’ role in operation oversight. This is accomplished by conducting a risk analysis to identify the most significant pipeline threats (e.g., corrosion, excavation-induced damage, material defects, etc.) followed by implementing periodic integrity assessments of those pipe segments. The frequency of periodic assessment is commensurate with the risk presented by each pipe segment. Inspection is typically completed using an in-line inspection tool, also known as “smart pigs”^c, to evaluate pipe integrity (e.g., wall thickness). Other preventative and mitigative measures may also be used to address the threats identified by risk analysis. These measures may include corrosion control monitoring and online leak detection, both forms of condition monitoring technologies.

49 CFR Part 195.452 also identifies the type, timeline, and degree of response required by the operator at the onset of detection. The regulation identifies various timeline conditions after a defect is detected in the pipeline, from immediate repair condition, 60-day condition, 180-day condition, and other conditions.

^c A device that travels along the interior of a pipeline attached with cameras and other sensing equipment.

Each timeline is conditioned on the extent of damage. For example, given a metal loss of 80% of the nominal pipe wall material, an operator must temporarily reduce operating pressure of (or shut down) the damaged pipe section. This is in addition to repairing the section as soon as possible. Contrasting, a minor damage event (e.g., a dent of 2% pipe diameter) requires repair within 180 days; reduced operation is not necessary. Specifics of the degradation type are also provided. For the 180-day condition, the damage can include one of the following. Note, only 5 of 9 conditions are listed for example purposes.

- (1) Dent with depth greater than 2% of pipeline diameter (or greater than 0.250 inches for small pipes) that affects pipe curvature at a girth weld or longitudinal seam weld,
- (2) Dent located on the top of the pipeline (above 4 and 8 o'clock position) with a depth greater than 2% (or greater than 0.250 inches for small pipes),
- (3) Dent located on the bottom of the pipeline with a depth greater than 6% of pipeline diameter,
- (4) General corrosion in the area with a predicted metal loss greater than 50% of nominal wall,
- (5) A calculation of the remaining strength less than the current maximum operating pressure,

The benefit of clear delineation of requirements and degradation severity within regulations (such as those in 49 CFR Part 195.452) may provide clearer guidance to industry on how to address operational occurrence to be compliant. A detected degradation may be matched with one of the conditions listed and the corresponding response can be enacted by the operator. Interestingly, regulations incorporated through references (i.e., ASME/ANSI B31G) are limited. This may reduce operator confusion when applying the correct response action as much of the process is listed in the regulations (as opposed to cross-referencing other standards that may conflict). Note that while condition monitoring of pipelines is not explicitly mentioned in the 49 CFR, an operator may implement equivalent technologies that enable understanding of the condition of the pipeline.

The requirements identified in the IMP (Part 195.452) are examples of graded response based on detected defect severity. For condition monitoring of NPP SSCs, a similar graded response may be taken commensurate with the degree of damage detected by the monitoring program. However, note that specificity of pipeline degradation is not necessarily directly translatable to NPP SSCs; a similar analog would need to be developed for NPP SSCs.

3.2.4 Success Stories

In this section, success stories where non-nuclear industry implements a RIGA or similar approaches are presented. The intention is to illustrate the state-of-the-art in other industries and potential technology/methodology that can be applied to the nuclear industry.

3.2.4.1 Monitoring of Bridge Eyebars via Acoustic Emission Monitoring

Following the discovery of significant cracks and corrosion in the eyebars of the San Francisco Oakland Bay Bridge (SFOBB) [21] in 2009, the California Department of Transportation initiated a reconstruction of the bridge [22]. Figure 5 showcases one of the eyebar failures with a 12-inch crack along the support bar. The new bridge implements SHM in the form of an acoustic emission monitoring program of the eyebar length for early detection of degradation and cracks. The SHM complements the existing quarterly inspection process, specifically in critical areas that are difficult to inspect. In total, 640 acoustic emission sensors were installed on 384 eyebars of the SFOBB [22], providing 24/7 remote monitoring. Acoustic emission sensing is passive in nature, where the instrumentation is comprised of a wave generator and a sensor. A representation can be found in Figure 6. The sensor is intended to detect high-frequency elastic waves emitted by materials under stress, which indicate cracking, corrosion, or other issues. The acoustic emission monitoring program for the SFOBB sensors was used for the early detection of structural issues, facilitating timely maintenance activities.



Figure 5. Example of eyebar showing crack and failure location. Reproduced from [21].

The primary objective of the system is to [21]:

- 1) Detect crack location accuracy within ± 18 in. of the physical crack location,
- 2) Detect potential cracks at a size of 0.1 in., and
- 3) Demonstrate performance and capabilities of the monitoring system under background noise.

Establishing and installing the condition monitoring system involved several key steps: (1) proof of demonstration of capabilities of the acoustic emission method and equipment; (2) development of a pattern recognition algorithm and classifier for automatic detection of the onset of degradation; (3) acquiring baseline data specific to the bridge configuration; and verification of sensor operation via the pencil lead

break test^d [21]. Each system can also be accessed remotely for software upgrades, configuration changes, and remote reboot. Data may also be downloaded for data summarization and activity.

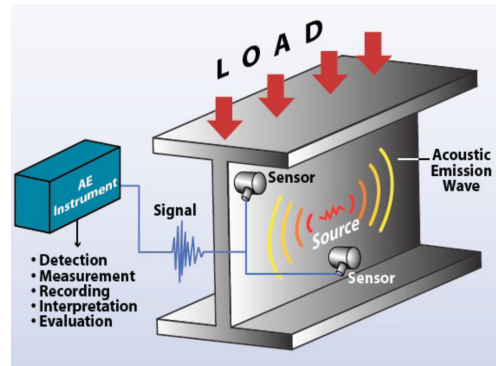


Figure 6. Acoustic Monitoring Schematic. Reproduced from [22].

There were several lessons learned from the application of acoustic emission monitoring [22]. One significant lesson learned was that every structure will have unique design characteristics that affect the response pattern; the same baseline data may not be used even for adjacent sensors. Furthermore, the method of installation may impact the response pattern. The sensing element and cables may not be installed using welds, holes (for mounting), or any other method that alters the shape of the eyebar [22]. Significant caution should be placed during installation as even small errors may result in false positives. For example, a piece of tape to hold the sensor cable and eyebar together flapping in high winds may generate comparable high frequency signatures to material cracking leading to false positive detections [22]. Significant background noise was another challenge during implementation, where improper deployment of the sensor may require significant data cleaning and experienced personnel for degradation detection. This challenge may be overcome through the proper selection of sensor technical specifications (e.g., frequencies, the number of sensors used, etc.) [22]. Lastly, installation and maintenance logistics of the project were also a concern. Namely, the instrumentation company may not necessarily be able to provide a turnkey system on large SHM projects without close cooperation and daily communication with the bridge owner. Therefore, a full safety and installation plan should be developed in partnership with the owners that consider the installation and operational conditions of the SHM (e.g., traffic volume over the bridge, time-of-day) [22].

Procurement was another significant challenge as conventional engineering procurement requires that the oversight body (i.e., California Department of Transportation) be knowledgeable about the monitoring system. This may be difficult, especially as the acoustic monitoring system utilizes proprietary components.

^d Breaking pencil lead against the structure generates a comparable acoustic noise that can be sensed by the monitoring system.

To overcome this difficulty, a performance-based requirement set may be used that establishes performance criteria based on a set of general technical specifications, software requirements, demonstration test, initial system testing, and maintenance procedures. For example, for the SFOBB [22], a proposed monitoring system must be able to:

- (1) Monitor the entire length of the eyebar on a continuous basis;
- (2) Propose a minimum crack size;
- (3) Propose a level of monitoring accuracy;
- (4) Have remote access (e.g., reboot, reconfiguration, software update, etc.);
- (5) Propose the use of a detection method (e.g., decision algorithm, source discrimination, etc.);
- (6) Demonstration of aforementioned criteria on a proof-of-concept test;
- (7) Demonstration of aforementioned criteria on the field deployed system.

Data management and transference was identified as another challenge. Specifically, the acoustic monitoring system generated vast volumes of data; using cellular or wireless communication for data transfer may not be adequate. For the SFOBB installation, fiber optic cables were installed to manage the high volumes of data traffic [22].

Since deployment of the acoustic monitoring system, real cracks have been detected on the SFOBB with follow-up action. For example, on Monday, July 16, 2012, an alarm notification was triggered by the acoustic monitoring system. After a secondary review of the data (via personnel), the potential of a crack was confirmed, and onsite bridge personnel were dispatched to inspect the location. A 1.5 in. electrical conduit rubbing against the eyebar wearing away 0.125 in. of the protective coating was discovered; the coating protects against eyebar corrosion. This condition was remediated by installing insulation on the conduit and has resulted in no new alarms from the location. A key observation from this event was that even with experienced inspectors, visual inspection alone may not have identified this degradation even under regular inspection cycles. This conclusion was determined as the rubbing location was considered “in plain sight” but partially visually blocked by the conduit itself. Follow-up assessment by the California Department of Transportation determined that eyebar corrosion would likely have resulted in a large stress concentration and eventually failure (similar to the crack detected in 2009). This detection is postulated to have saved \$14 million dollars, the cost of having eyebar head replaced if the monitoring system had not been installed. Several other alarms (both true positive and false positive events) have also been triggered since the installation of the system.

Acoustic monitoring has been shown to be successful at SHM. Similar deployments of acoustic emission structural health monitoring were also performed on the Carquinez suspension bridge [23].

3.2.4.2 Assessment of Bridge Condition via Risk-Based Inspection

Ref. [24] provides a discussion on bridge maintenance using risk-based inspection (RBI) that may be used for either the SFOBB or the Carquinez bridge (discussed in Ref. [24]). The RBI process identifies risk-based methods for determining timing of the next inspection. The intent of the RBI is to reduce the number of expensive and intrusive inspections while maintaining bridge reliability. The steps conducted in RBI are similar to conventional nuclear probabilistic risk analysis, where the hazards are identified and occurrence frequency determined, followed by a consequence analysis and determination of inspection interval and scope. However, rather than using exact failure probabilities of components, the RBI process uses a point system to determine the likelihood of failure, ranging from unlikely to very likely. Table 2 provides examples of the scoring system which identify how characteristics of bridge elements affect reliability. A higher score indicates higher susceptibility to failure and increased inspection requirements. For example, during cable inspection and based on the extent of scoring, either a walkthrough with visual notes on degradation may be performed, or a more invasive inspection, where individual strands are inspected by driving separating wedges through cable bundles. In this sense, the extent of the inspection action is conducted commensurate with the risk posed by the component, considering both environmental and condition monitoring results.

Table 2. Qualitative risk scoring based on component failure early indicators [24].

Component at Risk Scenario	Attribute	Scoring
Anchorage Water Penetration	Anchorage has existing water leaks and/or standing water present within the chamber	20
	Anchorage show evidence of previous water penetration onto strands	15
	Anchorage experiences high humidity levels and/or condensation but no standing water	10
	Anchorage is dry	0
Wire Coating	Bright wire (ungalvanized)	20
	Galvanized wire	10
Acoustic Emission Monitoring System	No AE system (or existing AE system has not been regularly maintained)	20
	AE system installed and properly maintained – increase in number of detected breaks	20
	AE system installed and properly maintained – number of detected breaks are at steady state	5

Importantly, this risk scoring method suggests that the acoustic emission system is not necessarily a critical deciding factor for when maintenance should be conducted. Rather, a successful bridge condition monitoring program will also derive evidence from periodic inspection to determine when maintenance activity should be performed. Additional information related to applying risk and reliability approaches for

bridge integrity predictions can also be found in Ref. [25] which identify best practices in managing bridge scour^e.

3.2.4.3 Monitoring of Timber Railroad Bridges via Wireless Displacement Sensors

All timber railroad bridges account for 24% of the current railroad inventory (by length) within the United States. Forecasts of railroad operations predict an increase in railcar weight; this is problematic as existing timber bridges are not designed for any load augmentation. In Ref. [26], the authors demonstrate how wireless displacement sensing instrumentation may be used to inform which bridges should be reinforced (or rebuilt) to accommodate the increased railcar load. As trains pass over timber bridges, vertical displacement caused by train wheels traveling over tributary regions can be measured. This vertical displacement can then be used to determine whether timber support structures exceed operational limits and the type of response action that should be implemented to mitigate potential damage. Figure 7 shows collected experimental measurements for a train passing over a timber bridge.

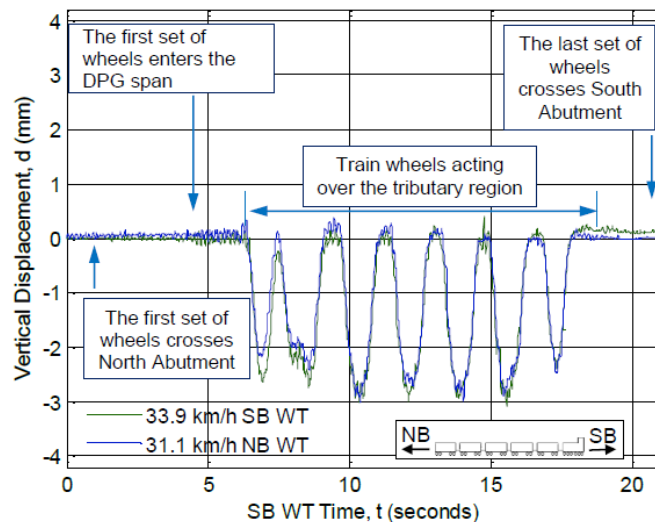


Figure 7. Measured vertical displacement of timber bridge support structures as train passes over tributary region. Reproduced from Ref. [26].

A fragility curve was used to determine service limit-states based on vertical displacement; a safety measure implemented by railway authorities to limit the potential mechanical impact on bridges. For example, a temporary slow order (TSO) may be implemented to temporarily reduce speeds for trains crossing temporarily vulnerable bridges. For bridges that are permanently susceptible without reinforcement, a permanent slow order (PSO) may be implemented. In Figure 8, a fragility curve is shown, where the x-axis plots the displacement relative to no-load condition, and the y-axis plots the probability of

^e Bridge scour refers to the removal of sediment around bridge abutments or piers by swift moving water which can erode the structural integrity of a bridge.

exceedance. H is the height of the support structure (i.e., pile bend). For example, a displacement of $H/125$ may be interpreted as 40% probability of exceedance. At this point, an inspection is highly recommended, and a TSO should be enacted to prevent further potential damage. Based on different displacements, a bridge service limit can be determined that can be used to guide train operations over the bridge (i.e., max bridge crossing speed).

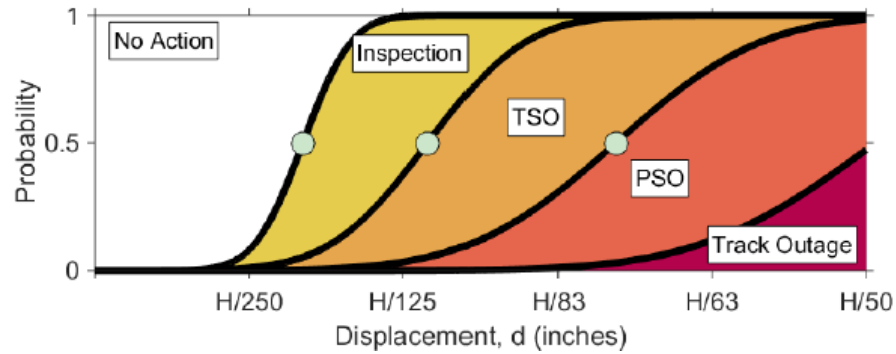


Figure 8. Fragility curve identifying train crossing speed for vulnerable timber rail bridges.

Reproduced from Ref. [26].

Due to limited data on service limits, the y-axis probabilities were determined by aggregating expert opinions on serviceability and safety limits. This data was then fitted using a lognormal distribution and applied as a cumulative probability distribution on the fragility curve. Based on the fragility curve and operational bridge data, decision prioritization of bridge repair/maintenance actions were completed on various timber rail bridges commensurate with the displacement.

Cost analysis using condition monitoring data may also be performed to determine the impact of service limits and the optimal moment a repair action should be performed. Figure 9 provides an example of how different service limits impact operational costs.

In this example, condition monitoring data from various bridges were used to determine the commensurate service limits for trains crossing wooden bridges to minimize the potential for exceedance.

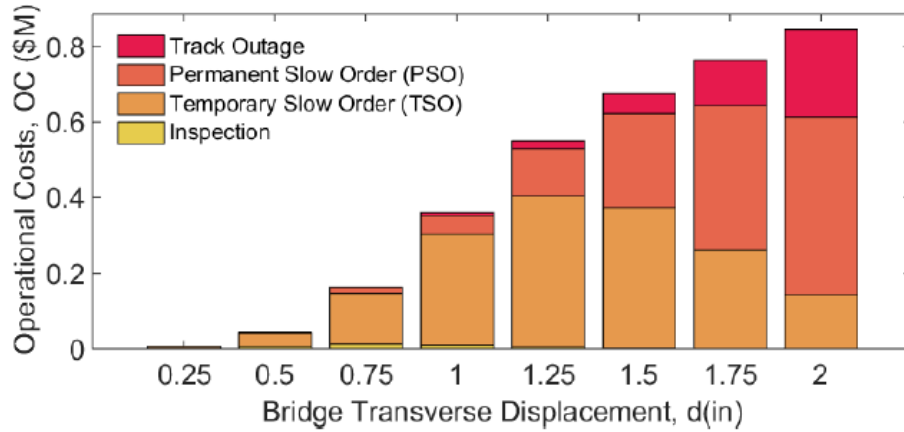


Figure 9. Operational cost distribution of different service limitations against transverse displacement.

Reproduced from Ref. [26].

4. APPLICATION OF RIGA FOR ACM

In this section, a workflow on the considerations for evaluating an ACM program in a risk-informed and graded process is presented in in Figure 10. The intent of the workflow is to capture the sources of information that may be considered when evaluating the grade of an ACM program and the types of actions that should be completed commensurate with the risk introduced by the program. The workflow begins with scoping, where an SSC is first selected to be a candidate for an ACM program. The functional and safety goals of the ACM program are identified next, followed by the details of the development process for the ACM program. Grade determination and grade quantification examines methods to develop the various grades applicable to an ACM program. Lastly, lifecycle activities examine potential subsequent operating and licensing actions that may be taken to modify the original grade determination and quantification. This workflow was developed by examining common features of other RIGA-like approaches adopted within the nuclear and non-nuclear industry. A detailed description of each step is provided in the following sections.

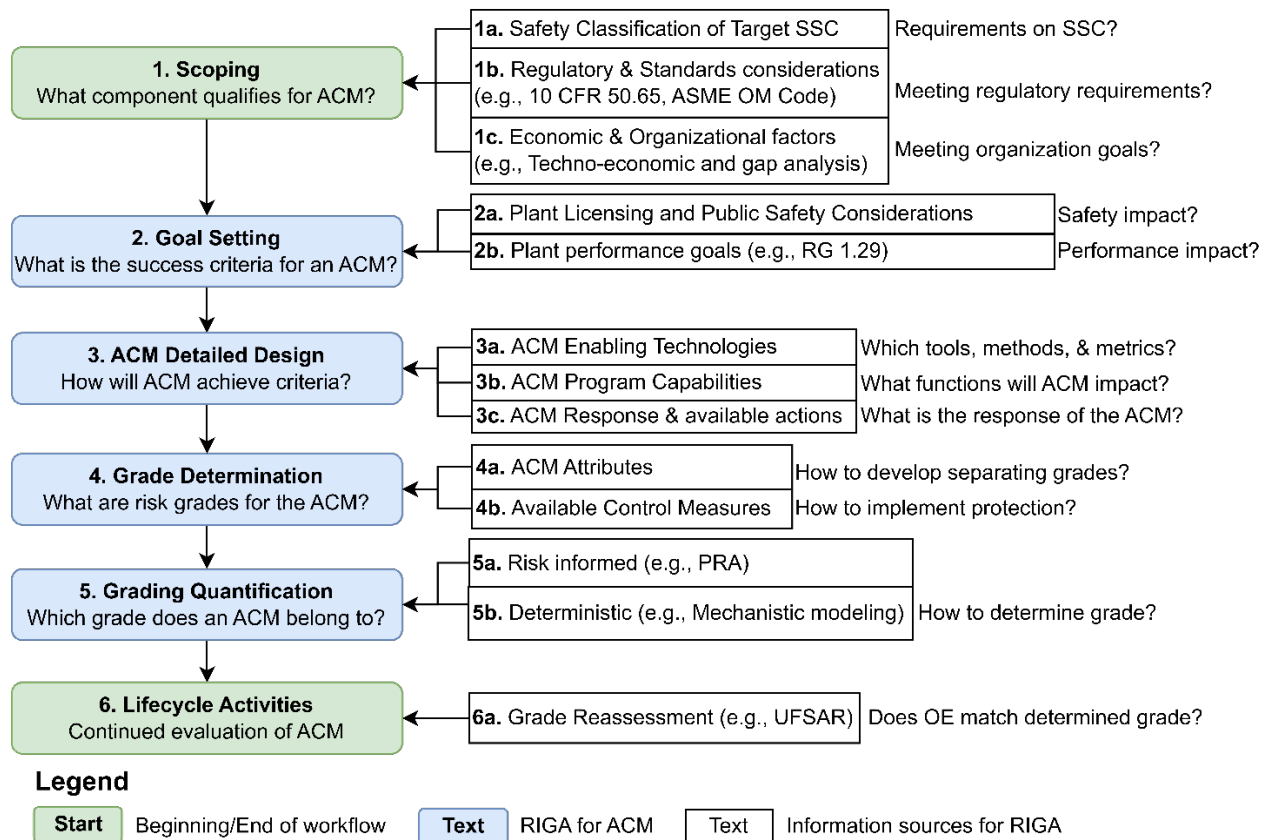


Figure 10. Generic RIGA workflow for establishing an ACM program.

4.1 Scoping

Scoping is the initiation and determination of the need for an ACM program for an SSC and the associated requirements for developing the program. Regulatory and organizational considerations both play a role in determining where and how an ACM program is developed, the capabilities, and the impact of the ACM program on the SSC (e.g., maintenance schedule modification). There are three key information sources that are considered in scoping: (4.1.1) SSC classification, (4.1.2) regulations and standards, and (4.1.3) economic and organizational factors.

4.1.1 SSC Classification

In nuclear power plants, public safety and consequence thresholds are intrinsically linked to the safety classification of SSCs and categorized based on their importance to safety, with classifications typically ranging from safety-related to non-safety-related (if using NEI 18-04). Note that this information source, while shown to be informing the scoping stage in Figure 10, may also be used in other stages. The use of SSC classification information is based on the premise that the modification of the procedures (e.g., maintenance scheduling and monitoring) of SSCs will influence their reliability and may impact plant safety

or performance goals. As safety-related SSCs are crucial for maintaining safe plant operation, they may also have more stringent design, maintenance, and monitoring requirements than lower safety class SSCs. For instance, the consequence thresholds for safety-related SSCs may be set at lower levels than non-safety SSCs due to their critical role in protecting public health and safety. SSC classification information may be derived from the final (or preliminary) safety evaluation report, or the master equipment list^f.

When developing an ACM program to monitor safety-related SSCs, the following considerations may play a role in evaluating the impact of the program:

- Impact on the SSC’s ability to maintain the integrity of the reactor coolant pressure boundary; or
- The capability for the SSC to shut down the reactor and maintain a safe shutdown condition; or
- The capability to prevent or mitigate the consequences of accidents that could result in exposure.

For non-safety related SSCs, there are several considerations for evaluating impact:

- Is the SSC relied on to mitigate accidents or transients? (e.g., fire suppression system)
- Is the SSC used in plant emergency operating procedures for mitigating functions?
- Will the failure of the SSC prevent a safety-related SSC from fulfilling their safety-related function? (e.g., non-safety-related condensate storage tank as water source for emergency core cooling system)
- Will the failure of the SSC cause a reactor scram or actuate safety systems? (e.g., turbine/generator & turbine trip as a transient initiator)

When developing an ACM program, considerations for how the program may impact the functionality of the SSC may be necessary.

4.1.2 Regulation and Standards

Certain regulations (e.g., 10 CFR 50.65, “Requirements for monitoring the effectiveness of maintenance at nuclear power plants”) require the monitoring of the performance or condition of select SSCs. Referenced standards through regulations, such as the ASME OM Code and its code cases, provide methodologies to conduct condition monitoring of components. Developing a RIGA process should consider the existing regulations and standards to prevent conflicting requirements on the implementation of an ACM program. The documents, and document sections, that are current related to developing condition monitoring (and may impact regulations on an ACM program) are as follows. Note that the list is not exhaustive.

^f Available if the evaluation is conducted on a DOE-site and not under the regulatory purview of the NRC.

- 10 CFR 50.65 [27] – Requirements for Monitoring the Effectiveness of Maintenance at Nuclear Power Plants
 - “...52.103(g) of this chapter, shall monitor the performance or condition of structures, systems, or components, against licensee-established goals, in a manner sufficient to provide reasonable assurance that these structures, systems, and components, as defined in paragraph (b) of this section, are capable of fulfilling their intended functions.”
- 10 CFR 50.34 [28]– Contents of Application – Technical Information
 - Licensees must submit a final safety analysis report that includes “(iv) Plans for conduct of normal operations, including maintenance, surveillance, and periodic testing of structures, systems, and components.”
- 10 CFR 52.79(a)(15) [29] – Technical Information in Final Safety Analysis Report
 - “(15) A description of the program, and its implementation, for monitoring the effectiveness of maintenance necessary to meet the requirements of § 50.65 of this chapter;”
- 10 CFR Part 50, Appendix B [30] – Quality Assurance Criteria for Nuclear Power Plants and Reprocessing Plants
 - “The pertinent requirements of this appendix apply to all activities affecting the safety-related functions of those structures, systems, and components; these activities include designing, purchasing, fabricating, handling, shipping, storing, cleaning, erecting, installing, inspecting, testing, operating, maintaining, repairing, refueling, and modifying.”
- 10 CFR 54.21 [31] – Contents of Application – Technical Information
 - “(3) For each structure and component identified in paragraph (a)(1) of this section, demonstrate that the effects of aging will be adequately managed so that the intended function(s) will be maintained consistent with the [current licensing basis] for the period of extended operation”
- IEEE 323-2003 [32] – Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations
 - “The principles, methods, and procedures described are intended to be used for qualifying equipment, maintaining and extending qualification, and updating qualification, as required, if the equipment is modified.”

- IEEE 338-2022 [33] – Standard for Criteria for the Periodic Surveillance Testing of Nuclear Power Generating Station Safety Systems
 - “The scope of periodic surveillance testing consists of functional tests and checks, calibration verification, and time response measurements, as required, to verify that the safety system performs its defined safety function.”
- RG 1.160 [34] – Monitoring the Effectiveness of Maintenance at Nuclear Power Plants
- EA 12-049 [35]– Order Modifying Licenses with Regard to Requirements for Mitigation Strategies for Beyond-Design-Basis External Events
- RG 1.187 [36]– Guidance for Implementation of 10 CFR 50.59, Changes, Tests, and Experiments
 - “...the process by which licensees, under certain conditions, may make changes to their facilities and procedures as described in the final safety analysis report...”
- ASME Boiler and Pressure Vessel Code [37]
- ASME Operation and Maintenance at Nuclear Power Plants (2022) [38]

In essence, the review process for an ACM program should consider existing standards and regulations; development of a new regulatory approach not based on existing information may conflict with existing guidance.

4.1.3 Economic & Organizational Considerations

From an organizational perspective, it is important to understand “why” an ACM program is being proposed. A techno-economic, environmental, and risk analysis (TERA) may be performed to answer such questions. A TERA can address organizational questions such as determining the near- and long-term cost-benefits of implementing an ACM program, the level of maturity of technology available for ACM programs (known as enabling technologies), and the impact to operational efficiency and/or meeting regulatory compliance on maintenance activities for SSCs (e.g., IST activities). While a TERA for ACM may not necessarily inform how RIGA may be developed for reviewing an ACM program, a TERA analysis provides the justification for the capabilities developed within an ACM program. For example, if a nuclear power plant operating organization discovers that an SSC frequently requires corrective maintenance, the organization might choose to implement an ACM program to advise on preventative action scheduling to reduce unanticipated maintenance outages, and improve overall plant performance.

4.2 Goal Setting

Goal setting is the development of the high-level design of the ACM program outlining the overall structure and architecture of the program. This design highlights how the program will meet associated regulations, standards, and requirements identified from scoping. Goal setting has two information sources: (4.2.1) plant licensing and public safety considerations, and (4.2.2) plant performance goals.

4.2.1 Plant Licensing and Public Safety Considerations

An ACM program may modify the maintenance schedule of an SSC, which might impact the reliability or safety function capability of the component. The degree of impact may consider the safety classification of the SSC, which are associated with the thresholds for radioactive release. As such, reviewing an ACM program should take into account the impact on the technical performance of the component in relation to consequence and release thresholds established by the SSC's classification.

For example, an ACM program may be used to justify the modification of an existing maintenance schedule from periodic to condition based. As the ACM program continuously monitors the system in place of manual monitoring procedures, engineers need to be careful not to become overly reliant on the system to determine when maintenance actions should be performed. Ref. [39] discusses how the automation of industrial processes may increase rather than reduce human errors. In essence, Ref. [39] discusses how automation may reduce an operator's familiarity and ability to conduct their task. When an operator is given opportunities to interact with a system, they develop implicit strategies specific to the component that improve the overall operation. Under automation, the opportunities to develop these implicit strategies are reduced with a higher reliance on established procedures or manuals, which may lack specificity to the system.

When evaluating an ACM program, the impact may be examined from a technical perspective (i.e., release thresholds) and from a human factors standpoint.

4.2.2 Plant Performance Goals

The overall intent of an ACM program is to improve plant performance. Plant performance may be separated into overall plant level performance goals and SSC specific goals [40]. Plant performance goals describe general criteria on the plant itself should an ACM program be implemented for an SSC. Existing plant performance criteria can be found in NEI 93-01 [40] and include:

- No unplanned reactor scrams per 7000 hours critical,
- No unplanned safety system actuation, or
- No unplanned capability loss factor.

Other performance criteria may include indicators similar to those recognized by NRC, industry organizations, or established by the utility if a plant-level performance criteria cannot be practically monitored.

An SSC specific performance goal may also be required if:

- The SSC is determined to be inherently unreliable; or
- A maintenance preventable functional failure (MPFF) caused an overall plant performance criteria to be exceeded; or
- An MPFF is the cause of a risk-significant or non-risk significant performance criteria to not be met; or
- A second MPFF of a similar cause occurs following the initial MPFF and generates the need for corrective action.

In essence, while an ACM program may have its own functional goals, the goals should need to be aligned with the plant level performance goals or SSC specific performance goals.

4.3 ACM Detailed Design

ACM detailed design is the engineering process where technologies and methods are selected to meet the requirements outlined in scoping and goal setting. ACM detailed design should consider (4.3.1) the role of novel and enabling technologies, (4.3.2) the capability of the ACM program when meeting functional requirements, and (4.3.3) the influence an ACM program may have on existing processes and procedures.

4.3.1 ACM Enabling Technologies

An ACM program may implement advanced technologies to improve NPP maintenance operations. These enabling technologies include, but are not limited to, advanced sensors and instrumentation (e.g., fiber optic sensing), predictive or forecasting models (e.g., machine learning and artificial intelligence), and natural language processing models (e.g., large language models). However, these technologies are not equivalent to each other, and each introduces a degree of uncertainty. As such, a RIGA process for reviewing ACM programs should consider how the maturity of a technology influences the type of CMs that need to be applied to minimize the risk contribution of the ACM program to the SSC. Additional details related to ACM enabling technologies can be found in Ref. [1, 2].

4.3.2 ACM Program Capability

Within detailed design, the exact functions of an ACM program are identified and how they will be implemented using models or algorithms is determined. However, different models and algorithms may be used to implement the same function in a similar fashion where different sensing technologies may meet

the same monitoring performance requirements. The core issue is that grading based on a specific technology, which offers granularity in evaluation, may limit technology inclusivity when the technology is improved or optimized in subsequent use or development.

A key example is the use of neural network models, which typically utilize mathematically ill-posed architectures. In essence, the functionality of a neural network model depends on the method of development (e.g., training data) rather than the shape and form of the architecture. A three-layer hidden feedforward neural network can, in practice, be generalized to any regression task given the relevant data. Rapid improvements in neural network technologies in the development process (e.g., Monte Carlo dropout) are expected. Managing and reviewing the development and optimization of these technologies may be too cumbersome given the rapid advancement of neural network methods.

An alternative approach, in contrast to examining specific technologies, is a graded approach based on the exact objectives and capabilities completed by the program on the target SSC. An ACM program may be broadly categorized into four capability groups, each describing a potential objective met by the program: monitoring, diagnostic, prognostic, and action planning. While diagnostics and prognostics are similar in nature, the key difference is that diagnostics is related to the current state of the SSC while prognostics is related to the future state of the SSC. Action planning is a more advanced capability and involves providing recommendations to the operator on future maintenance actions. A more detailed description of these groups can be found in Section 5.2.1.

4.3.3 ACM Program Response & Influence on Operator Action

Review of non-nuclear RIGA revealed that the response of an ACM program may also take a graded approach. For instance, given a detected minor degradation by a condition monitoring program, the immediate action may not be to schedule a preventative maintenance action but to supplement the monitoring with manual periodic inspection or to decrease the load on the SSC. In such instances, should an ACM program have graded response activities commensurate with the degree of degradation detected, the evaluation of the impact on delayed or modified maintenance, or modified operation, may be considered in the review process. Factors that may be considered when a graded response is proposed include:

- Impact of the timeliness of corrective or preventative action to restore SSC to compliance,
- Potential risks and consequences associated with continued operation under reduced load or modified conditions,
- Potential disruptions in plant operation or safety function caused by degraded operation of the SSC, and
- Impact on the plant's overall safety margins and defense-in-depth strategy.

4.4 Grade Determination

In the prior three stages, pertinent information regarding the design, target SSC, and function of the ACM program are collected. This information may be used to evaluate the grade of an ACM program. However, to grade an ACM program, a graded scale must first be developed commensurate with regulatory goals. As such, this section discusses how a grading framework may be established. A grading framework has two primary parts, grades and control measures. The grades specify unique and separate classes in which different ACM programs may be sorted. Grades represent situations where different control measures are needed to mitigate risk factors introduced by the ACM program. Control measures describe the technical, operational, or administrative features, functions, and capabilities for a component that may be implemented to mitigate risk. Developing a grading framework requires information on the (4.4.1) measurable or classifiable ACM attributes or characteristics, and (4.4.2) the available control measures that may be implemented and their effects.

4.4.1 ACM Attributes

An ACM attribute is a characteristic of an ACM program that is measurable or classifiable such that different programs may be identified separately by these attributes. Attributes may include qualitative or quantitative measures. The intent is that ACM programs with similar attributes may utilize the same set of control measures and represent an equal level of risk significance.

Selecting ACM attributes requires the identification of commonality between potentially different architectures and enabling technologies. This may require a common established agreement on the architectural requirements of an ACM program before a graded approach may be developed. Due to the novelty of ACM programs, a common agreement does not currently exist. However, other existing grading methods have utilized attributes such as:

- Design – The functional requirements of a system.
- Impact – The safety or reliability of impact of a system.
- Experience – The operating history and experience with a system.
- Management – The complexity of the management and maintenance of a system.
- Target component – The safety classification of the system.
- Material – The type and amount of radioactive material managed by the system.
- Technology – The specific technology or method utilized by the system.

Note that, regardless of the attributes selected, a grade in a RIGA process should represent a risk condition impacting plant safety or reliability. Grades do not have to scale linearly (as in the example of radioactive material management) and can identify different conditions that do not apply to each other.

4.4.2 Available Control Method

After the grades are determined, the corresponding control measures per grade should be developed. A control measure is an action that may be taken to reduce the risk of the program. They may involve technical, operational, or administrative procedures. A technical procedure may describe best engineering practices during the development of the ACM program. An operational procedure may describe the proper steps necessary to conduct the repair, service, and document work conducted on a system. An administrative procedure may describe planning, scheduling, oversight, and documentation of historical maintenance activities. Ultimately, however, different graded frameworks may have different interpretations on the appropriate control methods to implement. A close analog for ACM programs is from the “Digital Reliability Assessment Methodology” (DRAM) [41] developed by EPRI. DRAM develops a graded approach for digital system reliability analysis and provides a method to evaluate existing control measures in a manner that is consistent with their qualitative effectiveness. An entropy equation is proposed to conduct this evaluation, qualitatively scoring each control measure for their apparent effectiveness. DRAM also provides a method to evaluate how multiple control measures can be implemented within a specific grade. For instance, DRAM provides a method (i.e., combined control measure effectiveness) to evaluate when enough control measures are implemented that can sufficiently protect against an event under analysis.

The methodology identifies four different control measure types: (a) ad hoc, (b) policy, (c) plant procedure, and (d) technical (shown in Table 3).

Table 3. Control Measure Types, adapted from Ref. [41].

Control Measure Type	Characteristic
Ad Hoc	The method is implemented but not on a formal basis. The means of implementation is at the discretion of plant staff.
Policy	A formal policy is used to implement the control method. Plant staff are expected to comply with the policy, and it is enforced by plant leadership.
Plant Procedure	A formal procedure with steps is implemented as a control method. Plant staff are expected to use and adhere to the procedure.
Technical	The control methods are implemented into the equipment or via design. Technical control methods are maintained by a plant procedure.

Each control method type is also associated with a control method strength, which is the degree to which a control method may mitigate a specific event scenario. Four factors are considered in the evaluation of control measure strength:

- Protect – Control measure provides a means of prevention.
- Detect – Control measure provides a means of detection.
- Respond and Recover – Control measure provides a means of responding and recovering.
- Timeliness – The detect, respond, and recover characteristics of the control measure can occur before or after the event occurs.

The control measure strengths are listed from low, limited, moderate, and high, with increasing effectiveness. For each combination of control measure type and strength, DRAM provides a subject matter expert determined score value ranging from 0.10 to 3.00 (arbitrary scale), where 0.1 indicates least effective and 3.0 indicates most effective. Considerations for scoring are also provided, specifically where low strength and weak control measure types (i.e., Ad Hoc) cannot be scored to a higher effectiveness level than a high strength and strong control measure type (i.e., technical). Note that this scale and evaluation equation (i.e., entropy) was developed by plotting different interpretations by experts on existing engineering plant procedures using type and strength as its axes. The entropy equation was then fitted to the data.

One of the key reasons why this approach was adopted over reliability quantification (e.g., software reliability growth modeling) of the software systems is because there is no common agreement on the methods for measuring software reliability. Given that software reliability cannot be quantified, the true effectiveness of control measures cannot be determined. Ultimately, regardless of scoring, a minimum level of control measures will always be applied to any system. A licensee may credit their existing process to

meet this minimum level or may implement the control measures recommended by DRAM. Ref. [42] further recommends that a sensitivity analysis using fault tree analysis be conducted to ensure that the appropriate level of control measures is applied to mitigate potential failures of the ACM program.

When developing control measures for an ACM program graded framework, the following questions may be relevant:

- Which control measures are applied per grade?
- How can the effectiveness of a control measure be determined?
 - When multiple control measures are applied, how is the cumulative effectiveness determined?
- Are all control measures applicable to all ACM program architectures for a particular grade?
 - If not, how should applicable control measures be selected?
- For control methods that a licensee has already implemented within their development process and not within the graded framework, how will the effectiveness of these methods be determined?

4.5 Grade Quantification

Grade quantification involves examining an ACM program and quantifying its attributes such that a specific relevant grade can be selected. These attributes may be qualitative (e.g., capability classification) or quantitative (e.g., reliability) in nature. Note that grade determination and quantification are linked; developing the separation criteria for grades within a framework may also be used later to grade an ACM program. In essence, there are two sources of information that grade quantification may use (4.5.1) risk-informed methods, and (4.5.2) deterministic methods.

4.5.1 Risk-informed Methods

Risk-informed methods include but are not limited to methods involved in PRA such as fault tree and event tree analysis, risk reduction worth, margin analysis, etc. Conventional PRA methods to inform on maintenance are discussed in Ref. [43]. Specifically, the report provides detailed approaches for using PRA importance measures to rank SSCs and evaluate impact of inadequate maintenance. Fault tree analysis and minimal cutsets form the basis of these methods and are used to identify which SSCs may have a larger impact on plant performance (e.g., CDF). Note that the frequency of initiating events for the SSC is also used to calculate a CDF contribution.

For example, Ref. [43] provides Equation (1) as a method to calculate how component unavailability increases the CDF by a factor of ‘f’ if inadequate maintenance is conducted,

$$\Delta\text{CDF} = \sum_{i=1}^n r_i f + \sum_{i>j} r_{ij} f^2 + \dots + \sum_{i_1>i>i_k} r_{i_1-i_k} f^k \quad (1)$$

where r_i is the risk reduction importance of component i , r_{ij} is the joint risk reduction importance of components i and j , k is the maximum cutset length, and f is a general factor for evaluating program efficacy. In this approach, risk reduction importance refers to the cutset contribution to the overall CDF. Variations of risk reduction importance include the risk reduction worth, risk achievement worth, Fussell-Vesely, and 90% CDF. For example, given an SSC, the risk significance of a maintenance activity can be determined if its risk reduction importance contributes to at least 99.0 percent of the cumulative risk reduction importance [40].

An alternative to risk importance is risk unimportance, applicable to non-safety related SSCs. Risk unimportance identifies SSCs where their failure has little to no plant impact; maintenance of these activities is also risk unimportant and would not require a comprehensive evaluation. Note that risk unimportance can be developed from risk importance measures. Risk unimportance may be used to justify why development of an ACM program on the SSC does not require additional review actions.

Finally, note that risk information may not always be available for grade quantification. A lack of historical data on newer systems or processes, complexity of system interactions, and evolving threats in operation are some of the reasons why a comprehensive risk evaluation may not be possible.

4.5.2 Deterministic Methods

In such circumstances, where risk information is incomplete to make a full grade determination, deterministic analysis may be used to supplement areas of uncertainty. Deterministic analysis, which involves evaluation on predefined scenarios and conservative assumptions, can be utilized to address gaps where risk data are missing. A licensee may predict system behavior under specific conditions impacted by the ACM program, thereby providing additional insights into the impact and performance of the program.

First, deterministic analysis is conventionally used in safety analysis and are methods to confirm that the safety functions of an SSC can be met and are within adequate safety margins. Deterministic analysis is also used to determine the safety classification of an SSC, which may be used to determine the grade of an ACM program (additional discussion provided in Section 5). Deterministic methods are aimed at demonstrating that the barriers to the release of radioactive material from the plant will maintain their integrity to the extent required. Typically, these analyses focus on neutronic, thermohydraulic, thermomechanical, structural, and radiological aspects, implemented with the associated computational tools (e.g., RELAP5, TRAPCON, PANTHER, COBRA, etc.). These analyses may be further supplemented with testing and inspection of the target system. Typically, three categories of acceptance criteria may be

used to judge the acceptability of the analysis. They are based on safety (i.e., related to radiological consequences or barriers), design (i.e., limits for systems), and operational criteria (i.e., operational procedures for event sequences).

For example, under the safety criteria, four event conditions should be considered:

- (1) Normal operation,
- (2) Anticipated operational occurrences,
- (3) Design basis accidents, and
- (4) Design extension conditions, including sequences without significant fuel degradation and sequences with core melting.

An ACM program is anticipated to only have an impact on normal operation as its roles are related to the maintenance and operation of SSC. However, inadequate maintenance may result in an SSC being unable to perform its safety function. In such circumstances, a deterministic evaluation may be performed to show that the impacts of the program do not extend beyond normal operation. Postulated initiating events over the use of the ACM program may be considered, where failure modes of the ACM program are evaluated for their impact on the SSC. These failure modes may be derived from a failure modes and effects analysis of the ACM program and target SSC. In this respect, an ACM program may be graded by the type of event sequences impacted by the program.

4.6 Lifecycle Activities

Given the limited operational experience with ACM programs and the novel technologies introduced, the initial expectations on the performance of the program in comparison to the real performance might not be aligned. The regulatory review of these initial expectations may also not be aligned with actual program performance. In such circumstances, a grade reassessment may be required to identify whether the initial grading matches the operational conditions.

4.6.1 Program Performance Data

Evaluation of the effectiveness of a condition monitoring program may follow RG 1.160 [34]. This regulatory guide describes methods that are acceptable for demonstrating compliance with 10 CFR 50.65 (i.e., Maintenance Rule). NUMARC 93-01 [40] is one such method that describes the use of maintenance-preventable function failures^g (MPFF) as an indicator for reliability. MPFF is also used to validate that the actions of the condition monitoring program are effective. In this case, MPFF may compare the events pre-

^g MPFF is an unintended event or condition such that an SSC is not capable of performing its intended function and should have been prevented by the utility performing the appropriate maintenance actions.

and post-implementation of the ACM program to evaluate the efficacy of the program. Alternatively, RG 1.160 [34], Section 2 specifies that, for some SSCs, an MPFF performance criterion may be too small to be effectively modeled and trended as required by the rule (i.e., insufficient data). In these cases, the licensee should establish performance or monitoring criteria to demonstrate that the program is effective. In either case, ACM program performance data may be required to evaluate that the initial grading matches operational experience.

5. GRADING FRAMEWORK DEVELOPMENT CONSIDERATIONS

This section discusses considerations when developing a RIGA to support regulatory review of ACM programs. Different potential methods to implement a grading framework are provided to discuss the individual considerations for each approach. Specifically, how qualitative or quantitative attributes of the ACM program may be measured during grading and the specific considerations needed for each method. The methods presented are developed for grade determination and grade quantification from the workflow in Figure 10. For each grade, a commensurate level of control measures is identified and color-coded, ranging from *not allowed* (red), *stringent* (pink), *enhanced* (orange), *standard* (yellow), and *simplified* (green). Note that the exact control measures to be conducted per grade level are not specified and not within the scope of this work; the grades are defined arbitrarily. Lastly, while specific grade levels do not specify which control measures need to be applied, how grades are assigned (known as a grading rule) can be determined if guidance in regulation exists, or if a certain consistency is enforced. Grading rules are discussed in more detail for each framework.

5.1 Impact & Reliability Grading Only

This approach utilizes existing endorsed methods (e.g., RG 1.174 [44]) to develop a graded framework for ACM. Two different approaches are presented based on RG 1.174 [44] and IEC 61508 [45]. RG 1.174 discusses the use of risk-informed guidance when reviewing changes in plant design and operation. Note that RG 1.174 applies to light water reactor licensees, therefore, an applicant for an advanced reactor might need to request use of RG 1.174. Two metrics are presented in RG 1.174 and utilized when developing this framework, total core damage frequency (CDF) and change in CDF (Δ CDF) [44]. To grade an ACM program, the Δ CDF contribution of the program is first calculated. This value is then applied to the current CDF contribution of the component monitored. Table 4 illustrates how Δ CDF and CDF are used to grade an ACM program.

Table 4. ACM Program grading based on the impact to plant safety under RG. 1.174 [44].

Total CDF	Impact to Plant Safety (ΔCDF)				
	$\Delta \leq 1E-7$	$1E-7 \leq \Delta < 1E-6$	$1E-6 \leq \Delta < 1E-5$	$1E-5 \leq \Delta < 1E-4$	$1E-4 \leq \Delta$
1E-6	D	C	B	A	Not Allowed
1E-5	D	C	B	A	Not Allowed
1E-4	D	C	A	Not Allowed	Not Allowed
1E-3	A	A	Not Allowed	Not Allowed	Not Allowed

*Grade D: simplified; Grade C: standard; Grade B: enhanced; Grade A: stringent.

The grading rule (i.e., how grades are distributed in the table) applied to the framework from Table 4 is derived from RG 1.174 specified regions (Region 1, Region II, and Region III) and also based on the total CDF and the ΔCDF . As background, Region I does not permit changes to the design (i.e., the implementation of an ACM program), while Regions II and III permit changes. Figure 11 shows one potential grading rule based on the regions defined in RG 1.174. Color grading in Figure 11 matches color grading in Table 4.

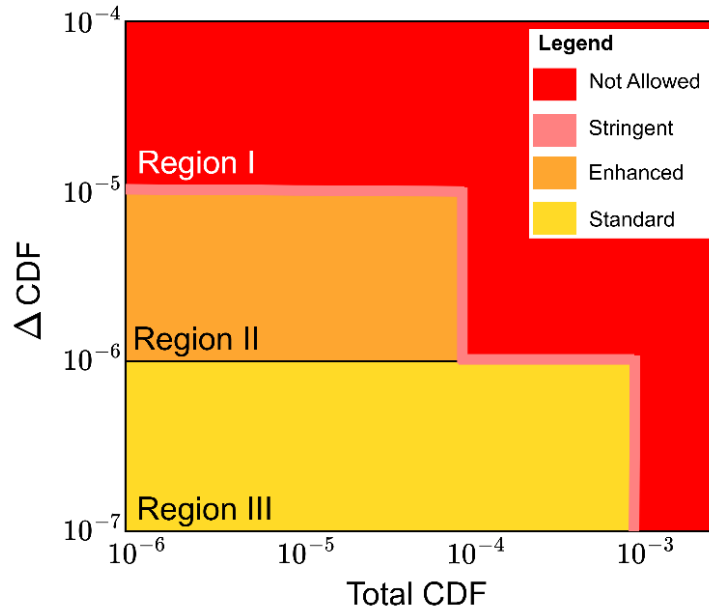


Figure 11. Grading rules based on RG 1.174 [44]. The simplified grade is not shown and assumed when ΔCDF is less than 10^{-7} .

IEC 61508 [45] is an international standard consisting of methods on the application, design, deployment, and maintenance of programmable electronic safety-related systems. Within IEC 61508, the standard identifies safety integrity levels (SILs) that define a target reliability of an SSC. For example, SIL 1 is the least stringent category with a continuous operational mode failure rate per hour between 10^{-6} and

10^{-5} . SIL 4 is the most stringent category with a failure rate per hour between 10^{-9} and 10^{-8} . Note that SIL are reliability targets for the SSC and not the actual reliability. As such, a vendor must show that a component meets an SIL category through deterministic testing and validation. In this grading approach, the ACM is graded by its impact to reliability, shown in the columns of Table 5, and the reliability requirement on the SSC monitored, shown in the rows of Table 5.

Table 5. ACM Program grading based on IEC 61508 [45] continuous mode reliability requirements.

SSC Reliability Class	Impact on SSC Failure Rate per Hour (ΔR)				
	$\Delta \leq 1E-8$	$1E-8 \leq \Delta < 1E-7$	$1E-7 \leq \Delta < 1E-6$	$1E-6 \leq \Delta < 1E-5$	$1E-5 \leq \Delta < 1E-4$
SIL 1	N/A	D	C	B	A
SIL 2	D	C	B	A	Not Allowed
SIL 3	C	B	A	Not Allowed	Not Allowed
SIL 4	B	A	Not Allowed	Not Allowed	Not Allowed

*Grade D: simplified; Grade C: standard; Grade B: enhanced; Grade A: stringent.

The grading rule applied to the framework in Table 5 is based on whether the magnitude in the change of the failure rate per hour is on par or less than the SIL specified reliability requirements. For example, for a reliability impact of an ACM program of $2E-5$ applied to an SIL 1 SSC (with calculated reliability of $3E-5$), the control measures applied would be stringent as the impact to SSC reliability is a substantial contributor to failure and has the potential to change the safety classification. For grades B, C, and D, the grading rule is established such that the magnitude of impact on reliability is approximately 1/10 (class B), 1/100 (class C), and 1/1000 (class D) of the failure rate per hour. For impacts less than class D, the impact may be considered negligible. Note that the lower bound may be extended until no further control measures are needed for the ACM program. For instance, ΔR less than $1E-10$ for SIL 4 classes.

5.1.1 Considerations

One prominent consideration in this grading framework is that it only examines the end result of the utilization of the ACM program, namely the impact to plant safety (e.g., ΔCDF). It does not explicitly consider the technology utilized in the ACM program, whether novel or established, the safety classification of the SSC, the functional objective of the ACM program, nor the process to develop or maintain the program. The framework implicitly considers these attributes, where it is assumed that the developer will assess these attributes in order to determine the impact to plant safety. For instance, if a maintenance action

is missed on a safety-related SSC due to a false negative prediction by the ACM program, it may have an impact on plant safety. To understand this impact, the licensee would need inherent knowledge of the safety class of the component, the behavior and faults of the model (for PRA modeling), the probability of ACM program failure, and the event sequences impacted. As such, this method of developing grading places more effort on the licensee side, where the regulator would only need to observe the outcome of the approach (also known as performance-based).

While these considerations persist, this framework is also the simplest to understand and implement, and the process to determine the impact to plant safety is known through existing PRA practices. However, given that an ACM program is a support system to an SSC, the impact to plant safety may be negligible or hard to quantify. Instead, failure of an ACM program may influence the reliability of the SSC rather than having an impact to plant safety.

Table 5 provides an example of how reliability grading can be conducted. The key premise of Table 5 is that the implementation of an ACM has the potential to decrease the overall reliability of the SSC. Considerations are similar for the framework developed for RG 1.174. However, the level of effort to deterministically quantify the reliability of the ACM program is likely to be resource intensive. In Butler et. al. [46], they show that to achieve ultrareliable values (10^{-7} or lower) in software systems, the literal time to test the system is generally intractable (i.e., to quantify 10^{-8} /hour failure rate requires more than 10^8 hours of testing). The implication is that the development of an ACM program for SIL 4 components may be intractable, and thus the corresponding grades generally unapplicable.

In both tables, where the level of impact is used to determine the grade of an ACM, the method of quantification is counter intuitive to the expected outcome of implementing an ACM program. For example, an ACM program may be established to increase the reliability of components through frequent monitoring and scheduling of preventative maintenance activities. As such, grading through the quantification of the negative impact of an ACM program may not be aligned with the actual impacts of the program. Under the current proposed framework (Table 4 and Table 5), if an ACM program improves component reliability, there is no guidance on types of control measures that should be applied. In this sense, the method of grade quantification must be aligned with the intended outcome of the ACM program. Using RG 1.174 or IEC 61508 to determine grade may not be aligned with program objectives.

Lastly, neither table considers how uncertainty in ACM technologies, whether through its usage, operational experience, complexity, or novelty, contributes to grading. Certain technologies, within the nuclear industry, have more established histories of use and experience over others (i.e., acoustic emission monitoring vs fiber optic temperature monitoring). Assigning similar grades to novel and established

technologies implies that the review process for both would be similar even if the technology utilized is not.

5.2 Capability Grading with Safety Classification & Reliability

To address some of the considerations identified in Section 5.1, rather than using quantitative values for the grading of an ACM program, a qualitative classification approach may be utilized based on an ACM program's implemented capabilities and the classification of the monitored SSC.

As a variety of technologies may be used to achieve the same condition monitoring objective, a qualitative classification on the capability of an ACM program may be used. The classes may include "monitoring", "diagnostics", "prognostics", and "action planning", where each class is differentiated by the objectives achieved by the ACM program. These classes are also ordered by the potential complexity of the model or system required to achieve each objective. For instance, to perform diagnostics, it is anticipated that some degree of monitoring capability will be required, otherwise the diagnostic model would not have sufficient information to perform diagnostics. The premise of this grading method is that more complex systems and models are required to implement more complex desired capabilities on the ACM program. With higher complexity, there is a higher likelihood that a software or model may contain a defect or vulnerability that may lead to failure. Refs. [47, 48] indicate a positive correlation between complexity metrics and vulnerability or software systems. These papers also discuss how cybersecurity may also be a concern for more complex systems. While this work does not explicitly consider cybersecurity, ACM program capability may be used as an analog to complexity, where more complex models may require a different set of control measures than less complex programs. As such, *capability* is an important potential grading axis.

The second grading axis for an ACM program is the function of the SSC being monitored, specifically, the SSC's role in maintaining safety within a plant system. This axis may be interpreted as the importance to safety of the monitored SSC. There are several regulatory documents that can determine the importance to safety of an SSC, such as 10 CFR 50.69 [49] (via risk-informed safety class RISC 1 through 4), NEI 18-04 [50] (via safety related, non-safety-related with special treatment, etc. classes), or IAEA SSG-30 [51] (via safety class 1 through 3). This work does not utilize specific classification from these documents but generalizes the classes into four arbitrary categories: low, medium, high, and critical. For example, a *Low* importance to safety SSC might not be involved in any event sequences, and has no impact on plant safety, in which case the application of an ACM program may not require additional regulatory oversight (other than existing requirements). In contrast, for a critical to safety SSC, modifications of the maintenance schedule or monitoring method might have significant consequences should a failure of the ACM program manifest, in which case, additional regulatory oversight may be required. An alternative to safety

classification is also presented based on IEC 61508 [45] reliability targets, shown in Table 7. While these two tables are nearly identical, reliability targets have a broader application, extending to importance to safety SSCs but also SSCs that have higher reliability requirements that may not necessarily have a safety impact.

Table 6. ACM Program grading based on a component’s importance to safety and capability.

ACM Capability	Importance to Safety of Monitored SSC*			
	Low	Medium	High	Critical
Monitoring	N/A	N/A	D	D
Diagnostics	N/A	D	C	C
Prognostics	N/A	D	C	B
Planning	N/A	C	B	A

*Grade D: simplified; Grade C: standard; Grade B: enhanced; Grade A: stringent.

Table 7. ACM Program grading based on reliability requirement on SSC.

ACM Capability	Required Reliability Target of SSC Monitored			
	SIL1	SIL2	SIL3	SIL4
Monitoring	N/A	N/A	D	D
Diagnostics	N/A	D	C	C
Prognostics	N/A	D	C	B
Planning	N/A	C	B	A

*Grade D: simplified; Grade C: standard; Grade B: enhanced; Grade A: stringent.

Note that the ACM user would need to develop grading rules for Table 6 and Table 7. Determination of capability grading is discussed in the next section.

5.2.1 ACM Capability & Complexity Assessment

On the capability grading axis, the definitions per grade are provided in Table 8. Note that capability refers to the functional objective of the ACM program rather than the NEI 18-04 [50] or RG 1.233 [52]

definitions of capability, which identify a capability as the ability for an SSC to prevent an initiating event from progressing to an event sequence.

Table 8. Determination of ACM program capability grade based on quantitative scoring.

Capability	Description	Complexity Score Range
Monitoring	Records or calculates observational data using sensing instrumentation information and sends to an operator. Program has no awareness of the state of the monitored system and does not distinguish degradations.	$LB < C < X_m$
Diagnostics	Utilizes recorded or calculated observational data to derive a conclusion about the current state of the monitored system. A conclusion may be a binary (e.g., “normal”, “degraded”) or multi-class (e.g., the type of defect). The state of a system must indicate information about a system’s performance; alarming is not considered diagnostics.	$X_m < C < X_D$
Prognostics	Utilizes recorded or calculated observational data to derive a conclusion about the future state of the monitored system. A prognosis may be triggered by a degraded diagnosis, but it is not a pre-requisite criterion. A prognosis of a future state could include the available margin until degradation (e.g., remaining useful life) or the future operating state of the system.	$X_D < C < X_P$
Action Planning	Utilizes recorded or calculated observational data to provide recommendations on the type of activity that will need to be performed on the system. An activity could include maintenance actions, reduced load, etc. Action planning may be triggered by diagnostics or prognostics, but neither are pre-requisite criteria.	$X_P < C < UB$

*LB = lower bound, UB = upper bound

The variables X_m , X_D , and X_P are the scoring ranges that are used to determine the respective capability grade of the ACM program. The variable C is the complexity score attained after evaluation of the ACM program. This evaluation is conducted by the licensee regarding what they understand the capability of the ACM program is. A reasonable justification would also be provided for why a score was achieved. A reviewer should examine this justification, make determination on adequacy, followed by using the

associated grade's control measures to evaluate whether the program is developed appropriately. To determine C , simple scoring equations, presented in Table 8 may be used. The intent of the specific scoring equations (and values attained) is that it ensures that ACM programs with higher capabilities cannot be scored to a lower capability. Table 9 provides an example of the scoring values. For example, any answer for basic diagnostic capabilities would automatically classify the system as *Diagnostic* or higher.

Table 9. Capability group question descriptions and equations to determine each question's score value.

Capability Group	Description	Capability Question Score Value Equation
Basic Monitoring Capabilities	Score for a single question under the basic monitoring category.	User defined (q_{MB})
Advanced Monitoring Capabilities	Score for a single question under the advanced monitoring category.	User defined (q_{MA})
Basic Diagnostic Capabilities	Score for a single question under the basic diagnostic category.	$q_{DB} = X_m = \sum_i^{N_{MB}} q_{i,MB}$
Advanced Diagnostic Capabilities	Score for a single question under the advanced diagnostic category.	User defined (q_{DA})
Basic Prognostic Capabilities	Score for a single question under the basic prognostic category.	$q_{PB} = X_D = N_{DB}X_m$
Advanced Prognostic Capabilities	Score for a single question under the advanced prognostic category.	User defined (q_{PA})
Basic Action Planning Capabilities	Score for a single question under the basic action planning category.	$q_{AB} = X_P = N_{PB}N_{DB}X_m$
Advanced Action Planning Capabilities	Score for a single question under the advanced action planning category.	User defined (q_{AA})

The parameter descriptions used to determine the scoring are shown in Table 10. These parameters are primarily related to how many questions exist for each capability category. A lower bound and upper must also be defined.

Table 10. Variable descriptions used in scoring.

Var.	Description	Equation
N_{MB}	Number of basic monitoring questions.	User defined
N_{MA}	Number of advanced monitoring questions.	User defined
N_{DB}	Number of basic diagnostic capability questions.	User defined
N_{DA}	Number of advanced diagnostic capability questions.	User defined
N_{PA}	Number of basic prognostic capability questions.	User defined
N_{PB}	Number of advanced prognostic capability questions.	User defined
N_{AB}	Number of basic action planning capability questions.	User defined
N_{AA}	Number of advanced action planning capability questions.	User defined
LB	Lower bound, minimum capability score.	Defined, default q_{MB} .
UB	Upper bound, maximum capability score.	Defined, default $N_{AB}q_{AB}$

In Table 11, an example of the type of questions that may be developed to grade an ACM program is presented. Note that the capability questions identify the functional objective of the ACM program and not the technology utilized. For instance, a neural network may be used to accomplish any capability; how the network is used determines the score and not the method or technology itself.

Table 11. Example capability questions and scoring for grading ACM programs.

Capability Group	Capability Question	Score Value
Basic Monitoring Capabilities	Analog sensing without digital processing.	1
	Analog-digital converter of analog signal or other digital processing.	1
	Calculation of intermediate values using sensing data.	1
Advanced Monitoring Capabilities	Real-time digital data storage and recall.	2
Basic Diagnostic Capabilities	Anomalous behavior detection with binary output; <i>anomalous</i> or <i>normal</i> .	3
	Degradation or fault detection with binary output; <i>fault</i> or <i>normal</i> .	3
	No cascaded data inputs; single diagnostic step with no data reuse.	3
Advanced Diagnostic Capabilities	Anomalous behavior detection with multi-class output.	6
	Degradation or fault detection with multi-class output.	6
	Multiple diagnostic steps; where the output of one model has multiple usages, such as feeding into more than one other model or will be monitored through the control room.	6

5.2.2 Considerations

There are several considerations related to the development and usage of the grading framework which are significant and cannot be overlooked if this framework is to be applied. In essence, the key considerations include (a) inconsistency in capability questions, (b) effectiveness of control measures under technology uncertainty, and (c) concern over reasonable assurance of completeness. Considerations of grading limits and scoring are also important but are considerations that would follow the previous considerations identified and not discussed.

First and foremost, the construction of the list of capability questions would require a level of technical expertise and familiarity with an ACM program that neither the licensee nor regulatory body may currently possess. Specifically, an ACM program might introduce new monitoring techniques and processing methods that are not well established with limited operational experience. In such circumstances, determining which questions should be used (and whether they are advanced or basic) when evaluating an ACM program can be contentious. For example, the use of large language models (LLMs). The application

of LLMs in non-nuclear industries has grown exponentially since its public introduction in 2023; they are also being proposed for maintenance and other activities at an NPP. Ref. [53] provides an example of how an LLM model may be used to review work orders and incident reports and provide a recommendation on maintenance activities. However, the authors also highlight that complex unstructured (e.g., bullet points) technical and potentially erroneous (e.g., spelling mistake) reports are a significant challenge when developing an effective model [53]. LLMs may include several hidden document preprocessing steps, such as stemming, tokenization, and lemmatization, that may further increase model complexity. Developing a list of concise capability questions that can sufficiently “encompass” the function of the LLM can be difficult.

This leads to the second concern when developing capability question-based grading. Namely, different technologies introduce different levels of uncertainty and complexity; applying the “correct” control measures for effectiveness across a variety of technologies can be difficult. For instance, two different models, one based on an ill-posed method (e.g., neural network) and the other on a well-posed method (e.g., multivariate state estimation technique [MSET]), may be used to accomplish the same condition monitoring objective. However, validation, transparency, reproducibility, and explainability between these two models are different. For example, neural networks are generally not very explainable. The choice of weights and biases within the network are not unique, such that different weights and biases may be used to achieve the same predictive performance. In contrast, MSET utilizes statistical and basic pattern recognition from previous plant data to make a prediction. This prediction can be traced back to the original reference data. As these two models accomplish the same condition monitoring task (and thus may be scored equivalently in terms of capability), control measures applicable to MSET may not be applicable to neural networks.

The last consideration is a culmination of the two previous considerations and their relationship to the overall objective of a RIGA process of regulating ACM programs. Specifically, a RIGA process is intended to utilize risk information to develop a grading. Neither a capability grade (i.e., monitoring, diagnostic, etc.) nor the capability questions reflect risk information. Different technologies might introduce different levels of risk even under the same capability grade. Without a quantitative assessment of the impact of an ACM program has on an SSC, this framework might not fully encapsulate the real risk of ACM program. Furthermore, determining the effectiveness of control measures developed per grade is difficult. In a comparative example, Ref. [42] provides a list of control measures to apply based on grading. A user is not required to implement all the control measures listed per grade. The number of control measures are then qualitatively scored to determine if enough measures have been applied. The effectiveness of control measures is not quantified and measures (per grade) are assumed to have equal potential in risk reduction. In essence, the consideration here is that when a RIGA process is generalized with grading (or scoring),

there is a loss of specificity of the technology under examination. This may introduce uncertainty when evaluating if the control methods and capability questions posed are appropriate and complete when evaluating a technology.

6. SUMMARY

The ACM programs are anticipated to enhance the safety, reliability, and efficiency of nuclear power plants. Developing a RIGA review process for ACM programs will ensure that the appropriate and commensurate level of control and evaluation is implemented without overburdening the ACM developers, while also maintaining the highest safety standards. Based on the extensive review of nuclear and non-nuclear risk informed and graded approaches conducted in this work, a RIGA process should contain the following aspects: (1) criteria for grading an item, (2) grades commensurate with the identified criteria, and (3) applicable control measures for risk mitigation per grade. This report provides a potential workflow on the types of information required to develop a RIGA process. This workflow identifies how different regulations and standards might influence the review process for an ACM program. In addition, four different example grading frameworks and their associated considerations are also provided.

Considerable interest exists in utilizing ACM to meet IST requirements and enhance operations and maintenance efficiency in nuclear facilities. The findings of the work outlined in this report will facilitate objective and rigorous assessment of ACM, thereby enabling the safe and efficient integration and application of ACM technologies.

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