Reliability and Integrity Management Program Implementation Approach

Svetlana Lawrence[a], Diego Mandelli[a], Todd Anselmi[a], and Curtis Smith[a]
[a] Idaho National Laboratory, Idaho Falls, USA
Svetlana.Lawrence@inl.gov, Diego.Mandelli@inl.gov, Todd.Anslemi@inl.gov, Curtis.Smith@inl.gov

Abstract: *Nuclear energy is the most reliable and environmentally sustainable energy source available today. In the United States (U.S.), nuclear-generated power accounts for approximately 20 percent of total electricity and over 55 percent of clean energy. New advanced reactors have enormous potential to help further decarbonize energy market, enhance grid resiliency, create new jobs, and build stronger economy. More than 50 new reactors are being developed in the U.S. and the Federal Government realizes an urgent need to deploy nuclear technologies to meet country's energy, environmental, and national security goals* [1]. *As such, the U.S. Department of Energy launched multiple programs to support advanced reactor deployment. The research described in this paper explores implementation strategies for Reliability and Integrity Management Program that directly supports the DOE goal to enable the near-term deployment of the advanced reactor technologies. The project is conducted under the Regulatory Development Program for advanced reactors sponsored by the U.S. Department of Energy.*

1. INTRODUCTION

Every nuclear power plant in the U.S. and around the world is obligated to maintain high levels of safety with measures that ensure plant reliability and integrity. These programs have become increasingly risk-informed in recent years. New reactor designs are very focused on risk-informed approaches to support all stages of development—from initial design and licensing to plant operation and retirement. The License Modernization Project (LMP) initiative by the U.S. Nuclear Regulatory Commission (NRC) is just one example of a risk-informed approach being encouraged for implementation.

The LMP initiative resulted in issuance of Regulatory Guide (RG) 1.233, "Guidance for a Technology-Inclusive, Risk-Informed, and Performance-Based Methodology to Inform the Licensing Basis and Content of Applications for Licenses, Certifications, and Approvals for Non-Light Water Reactors" [2]. RG 1.233 endorses Nuclear Energy Institute (NEI) 18-04, Revision 1, "Risk-Informed Performance-Based Guidance for Non-Light Water Reactor Licensing Basis Development" [3] as one acceptable method for non-LWR designers to use for selection of licensing basis events (LBEs); classification and special treatments of structures, systems, and components (SSCs); and assessment of defense-in-depth (DID), activities that are fundamental to the safe design of non-LWRs.

The NEI 18-04 document provides guidance for the following technology-inclusive, risk-informed, and performance-based (TI-RIPB) processes that must be completed to satisfy the requirements of RG 1.233:

- Systematic definition categorization, and evaluation of event sequences for selection of LBEs, which include Anticipated Operational Occurrences (AOOs), Design Basis Events (DBEs), Design Basis Accidents (DBAs), and Beyond Design Basis Events (BDBEs);
- Systematic safety classification of SSCs, development of performance requirements, and application of special treatments; and
- Guidelines for evaluation of defense-in-depth (DID) adequacy.

Some of the above processes are well-known since they were and still are used for licensing of LWRs, such as systematic definition and evaluation of event sequences and evaluation of DID. However, the third process—systematic safety classification of SSCs, development of performance requirements, and application of special treatments—is somewhat unfamiliar to LWRs. More specifically, development and monitoring of performance requirements is a completely new problem that does not exist in the

LWR domain. The reason is that development and monitoring of performance requirements is the essence of a performance-based approach, a methodology not yet fully embraced and employed by LWRs. While a performance-based approach for risk management is very beneficial, LWRs have historically leaned towards deterministic methods and only recently started shifting towards risk-informed approaches and in lesser degree to performance-based approaches. Given the novelty of the process, advanced reactor industry has an understandable difficulty in its interpretation and proper implementation. Fortunately, another industry initiative led by the American Society of Mechanical Engineers (ASME) has been in development for a few years—requirements for reliability and integrity management (RIM) program for nuclear power plants [4]. The objective of the RIM program is to define, evaluate, and implement strategies to ensure that performance requirements for SSCs are defined, achieved, and maintained throughout the plant lifetime. As such, the ASME RIM program fits extremely well with the objectives of the TI-RIPB approach described in RG 1.233 and given its acceptance by the NRC, can serve as an acceptable and satisfactory approach to address the process of systematic safety classification of SSCs, development of performance requirements, and application of special treatments.

In August 2020, the NRC communicated to ASME [5] that it has initiated efforts to review and endorse the 2019 Edition of ASME Boiler & Pressure Vessel Code (BPVC) Section XI, Division 2 [4] for application to non-light-water reactors (LWRs). Draft Regulatory Guide DG-1383 [6] was issued for public comments in September 2021 with full issuance expected in 2022. This endorsement adds urgency for developers of new reactor designs to understand how ASME Section XI, Division 2 is to be implemented.

Regulatory Guide DG-1383 "describes an approach that is acceptable to the staff of the NRC for the development and implementation of a preservice (PSI) and in-service (ISI) program for non-light water reactors." ASME Section XI, Division 2 also provides the requirements for the creation of the RIM program for any type of non-LWR nuclear power plant. The RIM program can be beneficial to the industry by reducing implementation costs and providing consistency in implementation for users. However, because ASME Section XI, Division 2 complies with ISI requirements through application of processes that are common to current LWR designs, there is limited experience to draw from and limited guidance on meeting the requirements for the development of the risk-informed RIM program.

Therefore, Idaho National Laboratory's (INL) Regulatory Development Research and Development (R&D) Program supporting the Department of Energy's (DOE) Office of Nuclear Energy initiated a project to develop guidance based on the pending ASME Section XI, Division 2 requirements for non-LWR developers through the establishment of the risk-informed RIM program. INL's project covers a limited scope focused on a few key steps:

- Plant, safety systems, and SSC reliability allocations
- Identification and evaluation of RIM strategies
- Evaluation of uncertainties.

The scope was selected based on industry feedback about the development of the RIM program and most urgent needs as related to the licensing process based on RG 1.233. INL's project demonstrates the RIM development process using a case study that presents various possibilities and options for meeting RIM program requirements, including considerations of a tradeoff between reliability and economics, and optimization of design options.

This paper presents activities, findings, and available outcomes of this project as well as identifies needs for additional research.

2. PROJECT DESCRIPTION

2.1. Scope and Objectives

The scope of this project is to develop a framework supporting RIM implementation strategies for advanced reactors. This work supports the establishment of a defined and predictable regulatory framework by providing guidance for implementing this NRC-endorsed portion of the ASME Code addressing the development of a RIM program.

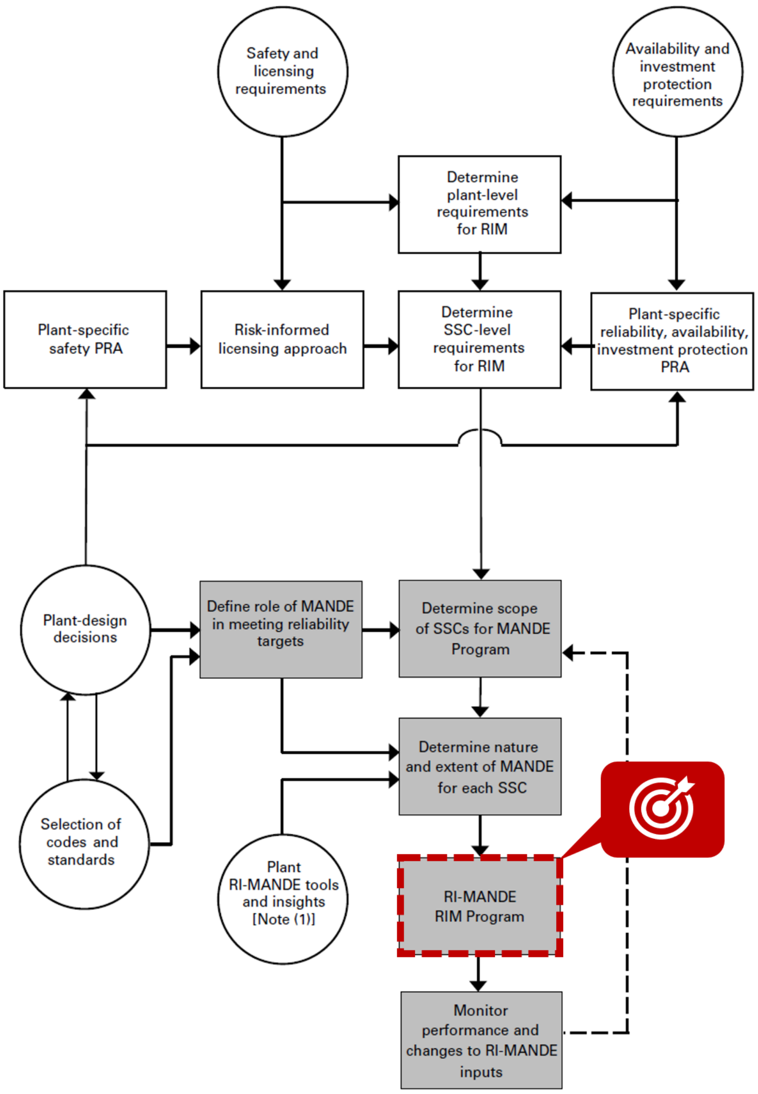
The objective of this project is to support the design and continuous performance assessment of advanced nuclear power reactors with a framework and a guidance document that provides directions on the use of reliability targets and RIM strategies as part of implementation of ASME Section XI, Division 2 based on risk-informed and performance-based approach to system performance management. The results obtained from this effort directly address the goal of enabling the deployment of advanced nuclear reactors by reducing the regulatory risks and uncertainties associated with their commercial deployment.

The outcome for this project is a framework that the nuclear power industry can use when developing ways to establish and meet reliability targets to comply with the requirements of ASME Section XI, Division 2. The future implementation of this framework will provide an ability to gain initial lessons learned as experience is gained in a RIM program strategies selection that can subsequently be factored into the development of a software tool that would expedite this process.

2.2. Description of RIM Program Development

Figure 1 presents the conceptual framework for a RIM program

Figure 1. RIM Program Conceptual Framework [4]



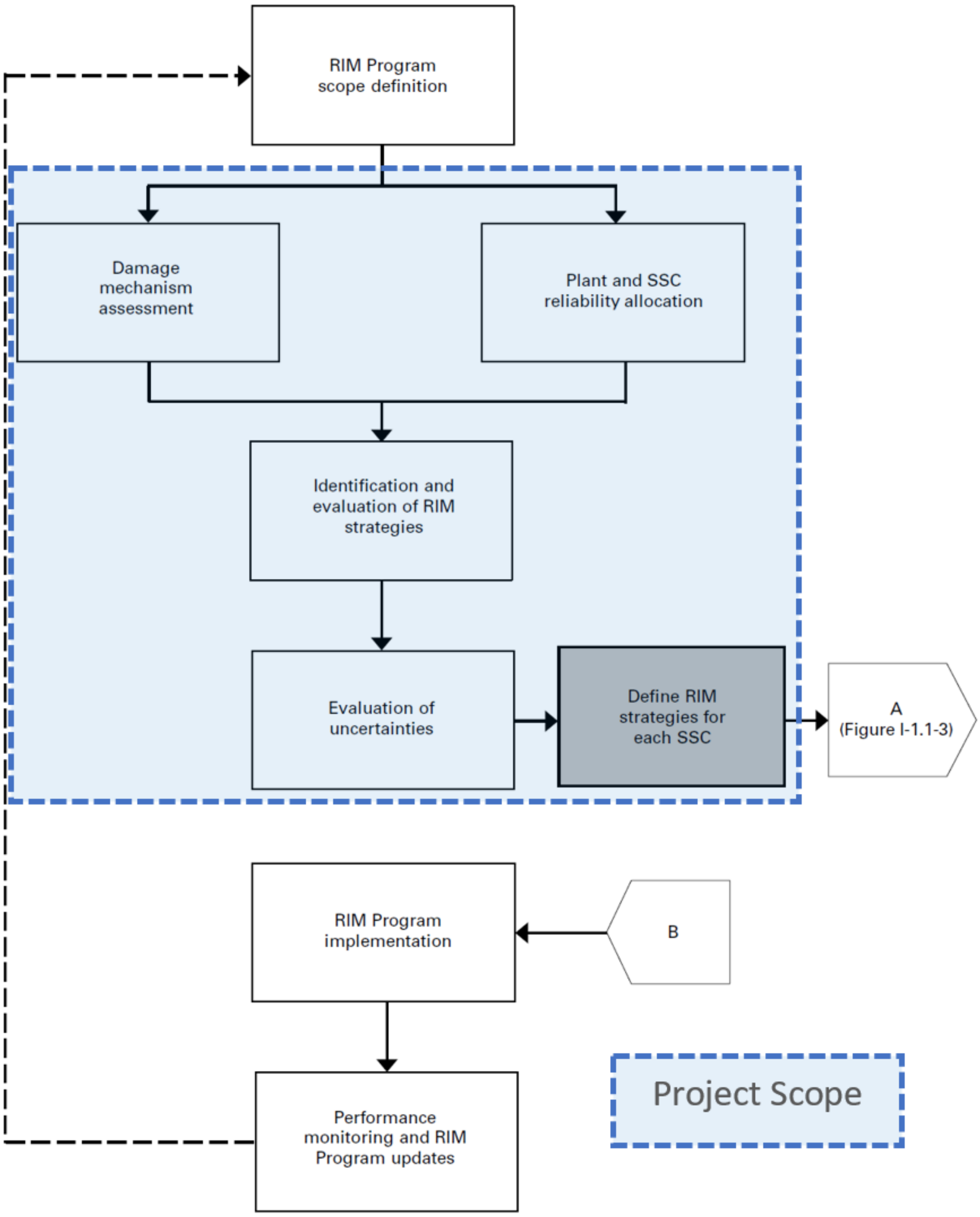
The development of RIM program requires determination of:

- WHAT to monitor/examine to meet the end-goal plant operational requirements (i.e., safety, investment protection, licensing), and
- HOW to monitor/examine the "selected what"

As the result of RIM program implementation, a RIM strategy is developed to monitor the performance of the system at each level, at either the complete system or multiple subsystems, and for each SSC.

The focus of the project is represented by ASME Section XI Division 2 Figure I-1.1-2 [4] presented as Figure 2 below. The outlined portions represent the scope to develop the initial RIM strategy based on the degradation mechanisms present, the allocation of reliability targets, and understanding the uncertainties of the non-destructive evaluation (NDE) assigned to a strategy.

Figure 2. RIM Program Scope and Project Scope



Each task in the RIM program development is very broad and complex; however, some tasks are more straightforward because they are similar to processes implemented by existing nuclear power plants (NPPs). For example, the damage mechanism assessment is a well-known process within the industry used in activities such as risk-informed in-service inspection (RI-ISI) and license renewal. While damage phenomena and mechanisms may be different between advanced reactors and LWRs, the process of their assessment follows similar steps.

Other tasks are more complicated because they are newly introduced in ASME Section XI, Division 2, or they use methodologies and approaches that are novel to the industry. Therefore, these tasks are selected as the focus of this project and are discussed below.

2.2.1. Plant and SSC Reliability Target Allocation

The reliability target allocation is a complex process because it involves consideration of multiple aspects largely grouped into two categories:

- Regulatory limits on the risks, frequencies, and radiological consequences of LBEs determined by the plant probabilistic risk assessment (PRA)
- Requirements for plant availability and investment protection defined by the limits on the risks related to the loss of production and/or loss of assets determined by the plant reliability, availability, investment protection PRA

The objective of selection of reliability targets is to establish a benchmark that will be used for evaluations of system performance. As such, reliability targets are developed during the initial phase of the RIM program and later the actual plant performance is measured against the reliability targets to identify deviations from the expected performance.

A simplified overview of the steps in the reliability target allocation process is presented below:

Step 1: Plant Level reliability targets, radiation dose limits. The starting point is the radiation dose limits to the public which are specified by the NEI 18-04 frequency-consequence curve. The radiation dose limits are the same regardless of reactor design but compared to LWRs, new designs may have additional requirements for dose limits due to different release sources.

Step 2: Plant Level reliability targets, accident scenarios. The accident scenarios are defined that could lead to a release associated with source terms identified in Step 1. The accident parameters include failure modes of SSCs and associated probabilities of failure which may lead to an accident. As the result of this step, frequency of each possible accident scenario is determined.

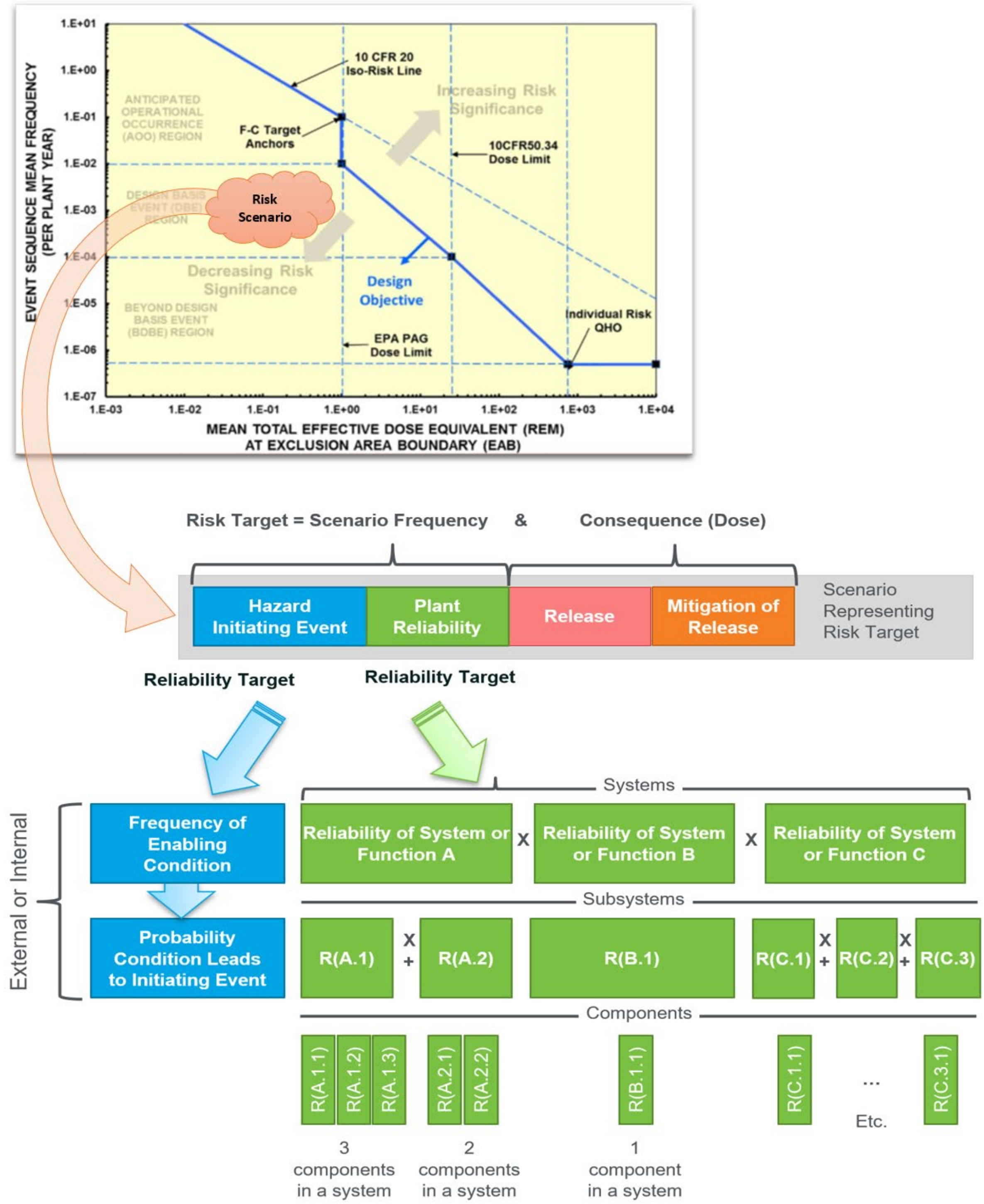
Step 3: System Level reliability targets. The reactor design must meet the radiation dose regulatory limits with various options to meet the requirement. Meaning one plant could accomplish it through high redundancy of mechanical systems (e.g., three train system) while another design may accomplish it through very high reliability of the primary system (e.g., passive cooling system) supported by a backup system for defense-in-depth. The system-level reliability targets are assigned in a way that the plant level reliability targets remain in the designated LBE category—AOO, DBE, and BDBE—including uncertainty considerations.

Step 4: Component Level reliability targets. This is the step where failure modes and failure probabilities are defined for each SSC to inform the SSC-level reliability targets. The SSC reliability targets are then input into the system-level reliability targets and the evaluation is performed to check if the initially-set system-level reliability targets are met. If not, SSC-level reliability targets are adjusted (i.e., reliability values increased) until the system-level reliability targets are satisfactory.

The difficulty with reliability target allocation is due to an uncertainty as to how much of a risk increase (or reliability decrease) each SSC can afford before regulatory limits in Steps 1 and 2 are compromised. This is a tricky question because an incremental risk increase for one SSC may not change anything at the plant level whereas the same small risk increase in multiple SSCs can have a detrimental effect.

Figure 3 presents a schematic of the reliability target allocation process which also demonstrates the previously mentioned difficulty where multiple options for reliability targets are available at each level.

Figure 3. Schematic of Reliability Target Allocation Process



2.2.2. *Damage Mechanism Assessment*

The material and operating conditions for an SSC are used to identify degradation mechanisms and associated failure modes that an SSC may be subject too.

Mandatory Appendix VII of ASME Section XI Division 2 provides supplements for different reactor types (many still in development). Similar to the approach taken for RI-ISI, the identified degradation mechanism attributes and attribute criteria within Appendix VII can be used to identify what the SSC may be susceptible too and where the area of interest for inspection/examination may best be applied.

2.2.3. Identification and Evaluation of RIM Strategies

The objectives of this task are:

1. Identify available RIM strategies that will meet the reliability targets
2. Evaluate and select combinations of strategies that are necessary and sufficient to meet and maintain reliability targets
3. Ensure that selected strategies are optimized in terms of both reliability and costs (i.e., meet reliability targets while using most cost-effective combinations of RIM strategies)

Objectives 1 and 2 are driven by system and/or SSC physical parameters (e.g., degradation mechanisms to consider, performance parameters to monitor). As such, they must be both necessary and sufficient to demonstrate that they meet regulatory requirements for reliability targets. However, selection of cost-effective RIM strategies is not a regulatory-driven but rather a desired objective. Many combinations would be available for a new reactor to meet reliability targets. This project focuses on providing the solution using multi-objective optimization techniques.

2.2.4. Evaluation of Uncertainties

The TI-RIPB licensing approach requires consideration of uncertainties. There are multiple sources of uncertainty associated with both the frequency and consequence estimates and equipment performance metrics are significant contributors to the overall uncertainty estimate. As such, it is important to properly identify, characterize, and account for uncertainties associated with equipment performance which can and should be accomplished as part of the RIM program scope.

Uncertainties from multiple sources should be included and propagated through the entire model quantification. This is explicitly accounted by using the INL-developed RAVEN software [7] which is a flexible and multi-purpose uncertainty quantification, regression analysis, probabilistic risk assessment, data analysis and model optimization platform.

2.2.5. RIM Strategies for Each SSC

In this project, the RIM strategies for each SSC are defined based on the optimization analysis where both system reliability and costs associated with various RIM strategies are considered.

3. RCCS RIM FRAMEWORK OVERVIEW

The initial framework was developed using publicly available information using a single simple system to demonstrate the concept of RIM strategy selection. The framework capabilities will be expanded to be applied to more complex systems and eventually to the entire plant.

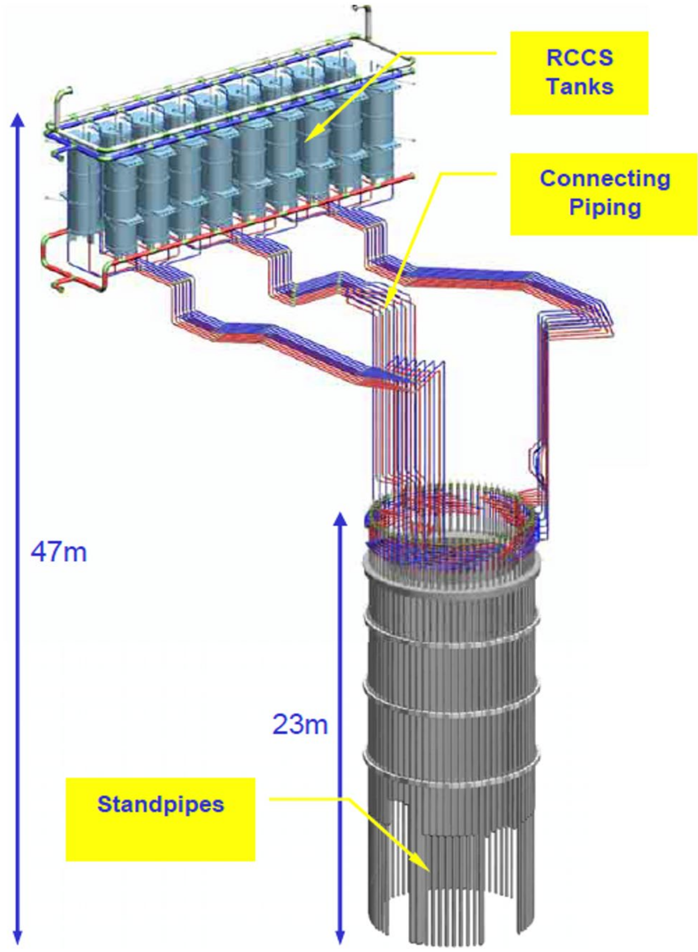
The system used for the initial framework demonstration is a reactor cavity cooling system (RCCS) for a high-temperature gas reactor (HTGR). The RCCS for the pebble bed modular reactor (PBMR) was used as the initial RCCS design. The pilot study performed for the PBMR passive component reliability and integrity management [8] was used as the starting point for the initial setup of the RIM framework developed in this project.

3.1. System Technical Description

The RCCS primary function is to remove thermal radiation from the reactor vessel and to release this heat to the atmosphere. A water-cooled RCCS design is used in this case. Failure of the RCCS does not pose nuclear safety concerns but the RCCS is relied upon for the defense-in-depth, and it should remain operable at all times. In addition, RCCS failure could cause flooding of the reactor cavity, an undesirable consequence in terms of availability and investment protection.

A simplified schematic of the RCCS design used in the initial framework is presented in Figure 4. Water flowing through the standpipes around the reactor vessel walls removes heat from the reactor vessel. Water is supplied from outdoor tanks via connecting pipes. Since the system failure mode that is of primary concern is a pipe/weld failure which leads to flooding of the reactor cavity, only a portion of the RCCS is considered which includes standing pipes and a fraction of connecting pipes. Therefore, there are only two groups of components, standing and connecting pipes, that are modeled in the RCCS RIM framework.

Figure 4. RCCS Schematic



3.2. RCCS RIM Strategies

3.2.1. RCCS Degradation Mechanisms

A RIM strategy is dependent on the type of degradation mechanisms that are present. Degradation mechanisms will vary for different materials in different operating environments and require different approaches to inspection, examination, and condition monitoring. Because the approach to degradation mechanism assessment (DMA) is more readily understood since it applies already commonly applied processes, this project did not include a formal DMA. For purposes of determining a RIM strategy, no specific degradation mechanism is included which subsequently allows for application of general NDE techniques.

3.2.2. RCCS RIM Strategies

For the scope of this work, as RIM strategy is defined as the combination of NDE and leak inspection strategies. Three NDE options are considered in the RCCS RIM framework:

- Phased Array with assumed simplified probability of detection (POD) = 0.5
- Eddy Current + Ultrasonic with assumed POD = 0.9
- Do Nothing, i.e., perform no NDE at all

The considered frequencies for the NDE options are 3, 6, 9, and 15 years.

The "do nothing" option, i.e., not doing any SSC monitoring, is included to evaluate its effect on system performance (measured as reliability) vs overall maintenance costs.

Three on-line leak detection (OLLD) options are considered:

- Visual examination with assumed POD = 0.5
- Imaging spectra with assumed POD = 0.9
- Do Nothing, i.e., perform no OLLD at all

The considered frequencies for the OLLD options are 1.5, 3.0, 4.5, and 6.0 years.

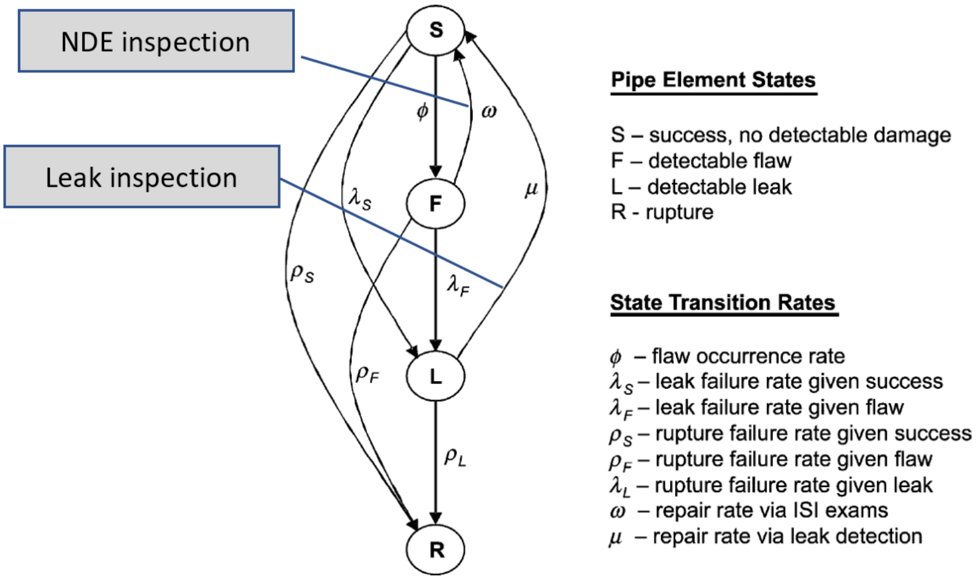
Although development of a RIM strategy focuses on achievement of meeting a desired reliability, costs can be considered when selecting from strategies that achieve the desired reliability since operations and maintenance (O&M) cost become a very important aspect of a successful long-term facility operation. Therefore, cost considerations are included in this evaluation. For the cost portion of the RIM model, both fixed and variable costs are considered. The fixed costs include things like personnel training and equipment costs. The variable costs are estimates for each inspection and they include trained personnel time, number of people to perform each inspection, supplies needed to perform the inspection, etc. Costs are evaluated for the lifespan of the plant which is assumed to be 60 years. The cost model is setup using a rate of $100 per hour to perform typical inspection activities. The following multipliers are used for the cost model:

- Visual examination: x 1.0
- Imaging spectra: x 2.0
- Phased array: x 2.0
- Eddy Current + Ultrasonic: 2.5

3.3. RCC Reliability Model

The RCCS RIM model uses a Markov model for predicting the effect from various inspection strategies on the RCCS piping reliability, an approach based on the research described in [9]. The schematic of the model is presented in Figure 5 with the frequency of pipe rupture defined in Equation 1 [9].

Figure 5. Pipe Markov Model



$$\rho_{ix} = \sum_{k=1}^{M_i} \rho_{ikx} = \sum_{k=1}^{M_i} \lambda_{ik} P_{ik}\{R_x|F\} I_{ik} \qquad (Equation\ 1)$$

Where:

ρ_{ix}	=	Total rupture frequency for pipe component *i* for rupture mode *x*
ρ_{ikx}	=	Rupture frequency of pipe component *i* due to damage mechanism *k* for rupture mode *x*
λ_{ik}	=	Failure rate of pipe component *i* due to damage mechanism *k*
$P_{ik}\{R_x\|F\}$	=	Conditional probability of rupture mode *x* given failure for pipe component *i* and damage mechanism *k*
M_i	=	Number of different damage mechanisms for component *i*
I_{ik}	=	Integrity management factor for component *i* and damage mechanism *k*; this factor adjusts the rupture frequency to account for variable integrity management strategies such as leak detection, volumetric NDE, in-service testing, etc. that might be different than the components in the service data

The failure rate of pipes λ_{ik} is given by Equation 2 [9]:

$$\lambda_{ik} = \frac{n_{ik}}{f_{ik} N_i T_i} \qquad (Equation\ 2)$$

Where:

n_{ik}	=	Number of failures (all modes including wall thinning, cracks, leaks and ruptures and any events in which pipe repair or replacement is made are included) events for pipe component *i* due to damage mechanism *k*
T_i	=	Total exposure time over which failure events were collected for pipe component *i* normally expressed in terms of reactor years

N_i = Number of components per reactor year that provided the observed pipe failures for component i

f_{ik} = Fraction of number of components of type i that are susceptible to failure from damage mechanism k for conditional failure rates given susceptibility to damage mechanism k, this parameter is set to 1 for unconditional failure rates

The repair rate ω and μ are estimated using Equation 3 and Equation 4 [9], respectively:

$$\omega = \frac{P_I P_{FD}}{(T_{FI} + T_R)} \qquad (Equation\ 3)$$

$$\mu = \frac{P_{LD}}{(T_{LI} + T_R)} \qquad (Equation\ 4)$$

Where:

ω = Flaw repair rate

μ = Leaks repair rate

P_I = Probability that a pipe with a flaw will be inspected in inspection interval

P_{FD} = Probability that a flaw will be detected given this segment is inspected

T_{FI} = Mean time between inspections for flaws, (inspection interval)

P_{LD} = Probability that the leak in the segment will be detected per inspection

T_{LI} = Mean time between inspections for leaks

T_R = Mean time to repair once detected

The reliability function for the RCCS piping is described by Equation 5:

$$R(t) = S(t) + F(t) + L(t) \qquad (Equation\ 5)$$

Where:

$R(t)$ = Reliability of a pipe over time t

$S(t)$ = Success, no detectable pipe damage over time t

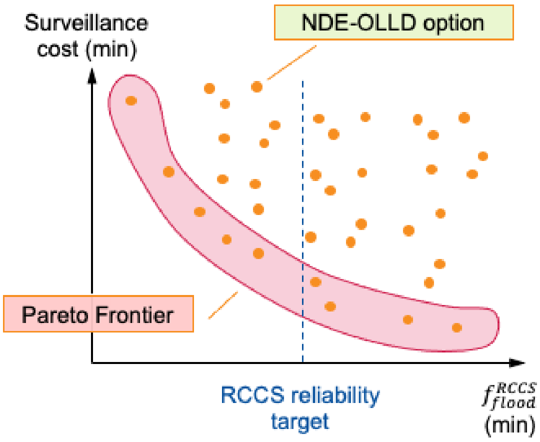
$F(t)$ = Flaw detected successfully over time t

$L(t)$ = Leak detected successfully over time t

4. RCCS RIM STRATEGIES EVALUATION

A RIM strategy is defined here as the combination of the RIM strategy associated to the connecting pipes and the RIM strategy associated to the standing pipes. For each pipe group, a RIM strategy is a combination of NDE and OLLD (i.e., leak) strategies. Given the chosen types of NDE and OLLD options indicated in Section 3.2, the total number of possible RIM strategies is 9801 [$(11x9)^2 = 9801$]. The choice of the optimal RIM strategies has been performed in a multi-objective optimization fashion where the objectives that need to be minimized are RCCS flooding frequency and RCCS surveillance costs. The RIM strategies that minimize both objective functions are identified in the Pareto Frontier as shown in Figure 6.

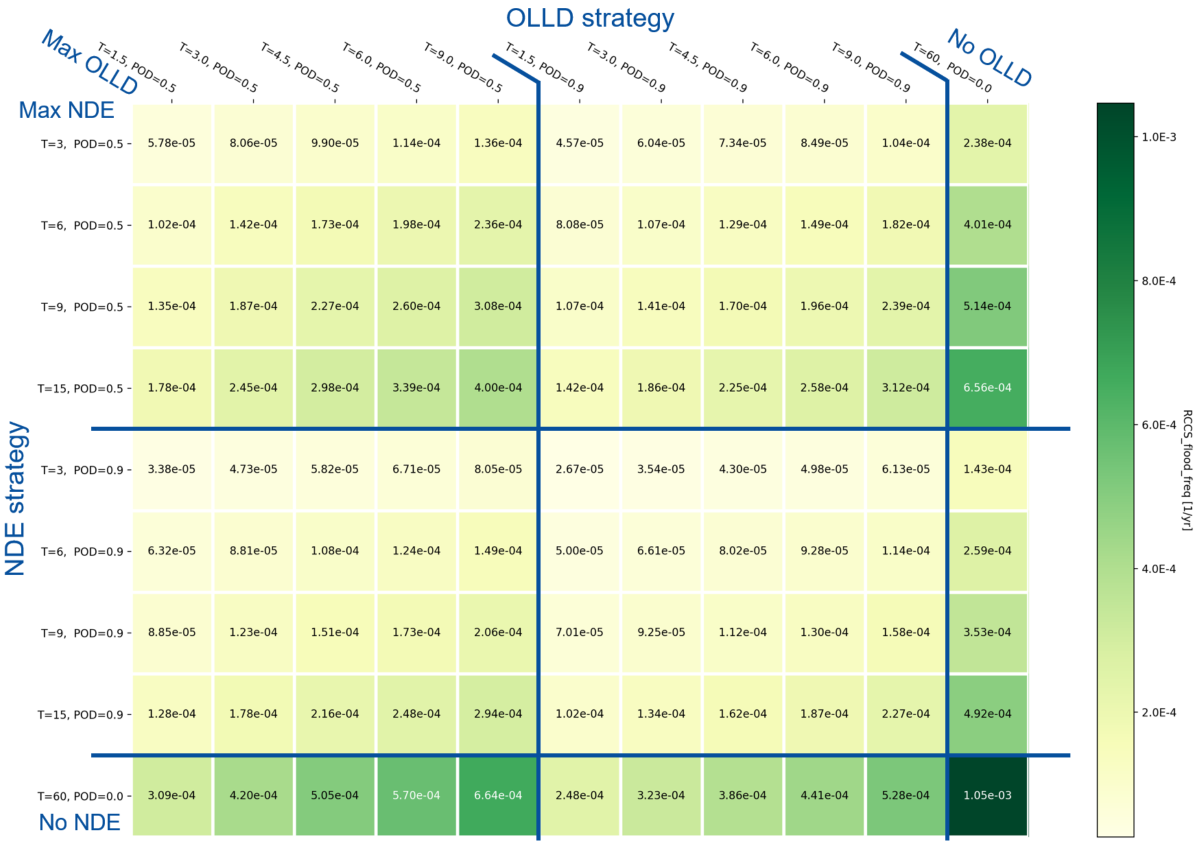
Figure 6. RCCS RIM Strategy Optimization



The uncertainty propagation was done for the optimal RIM strategies identified by Pareto Frontier distribution using RAVEN.

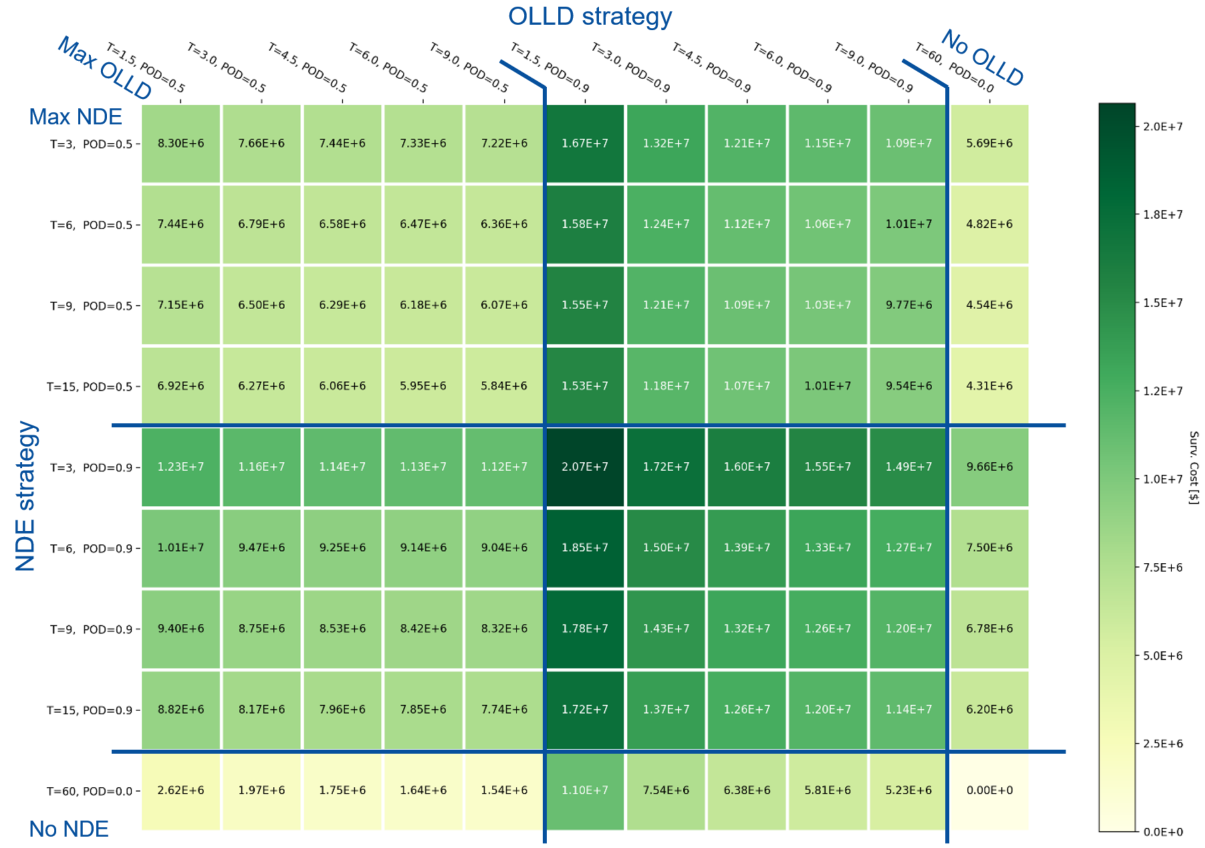
The preliminary results for the reliability values vs RIM strategies are shown in Figure 7 where it is assumed that same RIM strategies are followed for standing and connecting pipes.

Figure 7. RIM Strategies vs RCCS Reliability



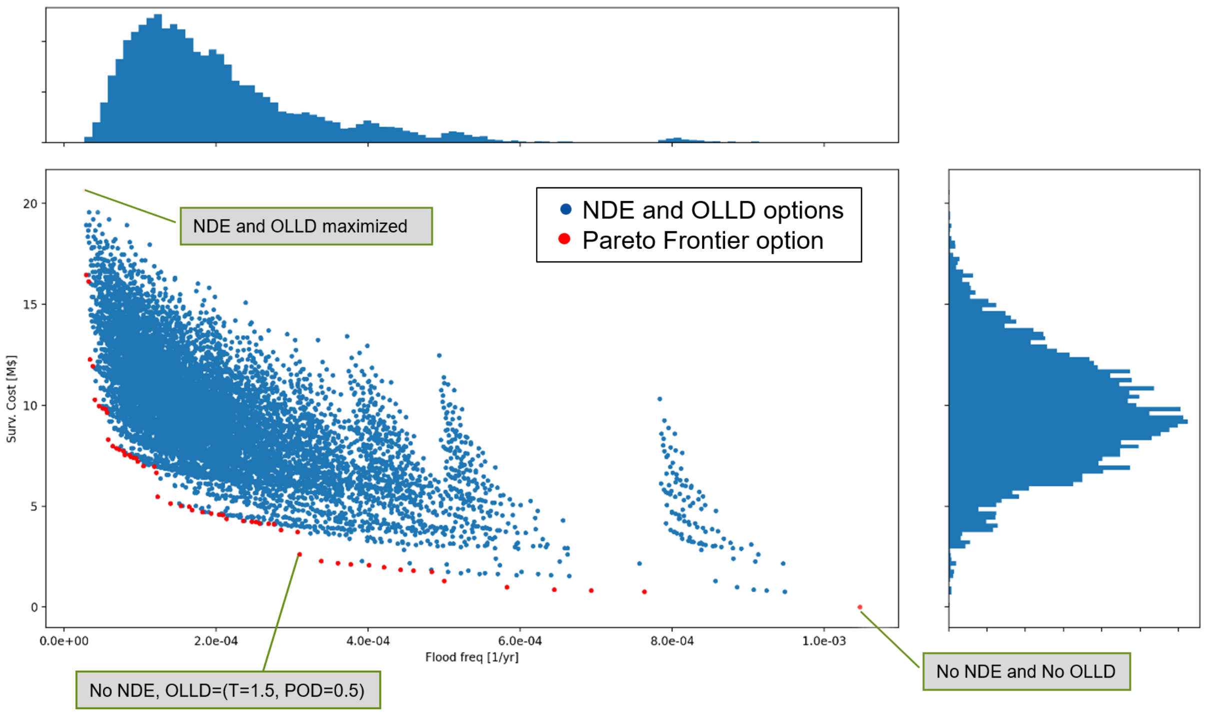
Similarly, the preliminary results for comparison of the surveillance costs over the lifespan of the plant (60 years) for the RIM strategies are shown in Figure 8.

Figure 8. RIM Strategies vs Surveillance Cost



The preliminary results for the complete multi-objective optimization of RIM strategies with flood frequency due to a pipe break vs surveillance costs are presented in Figure 9.

Figure 9. RIM Strategies: Flood Frequency vs Surveillance Costs



It should be noted that RIM strategies have relatively small impact on the overall system reliability determined in the initial RCCS RIM study. This is because pipe failure rates used for this initial evaluation are very low due to the generic data used for the analysis. In this evaluation, the pipe failure rates for a very robust LWR Reactor Cooling System are used. The framework will be adjusted to use more realistic data for pipe failure rates, probability of detection, and costs. However, the generic data was sufficient to demonstrate the capabilities and applicability of the framework.

4.1. Considerations for RIM Strategies Selection

The results demonstrated by the RIM framework are logical—the reliability of the system as well as surveillance costs increase when more robust RIM strategies are implemented and the "do nothing" RIM strategy obviously results in the lowest system reliability. However, the "do nothing" strategy does have associated costs measured in terms of a lost production, damaged facility, and expensive repairs. Because of the costs associated with these 'consequences' can influence the decision on what RIM strategy should be applied, the framework should be expanded to consider these costs.

The reliability data for new reactors is either limited or non-existent other than data developed from testing. This is a great concern because a lack of data associated with large uncertainties may result in overly conservative, i.e., excessively expensive, compensatory measures to overcome these uncertainties. One approach to deal with the data limitation is to rely on a performance-based approach and continuous monitoring to demonstrate adequate system performance. In this case, a traditional preventive maintenance strategy that new reactors may not be able to adequately plan for can be replaced with a condition-based maintenance approach. The benefit of the condition-based maintenance approach extends beyond the traditional O&M cost savings due to elimination of unnecessary maintenance. The greatest benefit for new reactors is the ability to adjust the condition-based O&M posture according to the plant / system actual performance. As such, it is important for the new reactor designers to consider future O&M options early in the design process to ensure that the reactor license allows these beneficial O&M options.

It is expected that with time, as operational data becomes available, maintenance strategies will be adjusted to better reflect degradation mechanisms, critical failure modes, and other contributors to system unreliability. Data obtained via system health monitoring can be used to prioritize maintenance activities based on the SSC performance margin rather than based on probability of failure values that are based on generic failure data. The RIM framework needs to be expanded to account for the future need to monitor system performance and make adjustments to the RIM strategies as needed given that the RIM program is a "living program" that represents as-built, as-operated plant where credit can be given for various improvements (e.g., added sensors improve monitoring capabilities).

Another consideration related to RIM strategies for new reactors can be referred to as "built-to-inspect". Meaning the plant should be designed in way that allows various RIM strategies. For example, a visual inspection will not be an option for equipment located in very harsh environment or in physically inaccessible areas. In this case, more expensive RIM strategies potentially with specialty equipment will be the only feasible options which may results in much higher O&M costs which could be avoided by a better design solution.

Consideration of different lifespan for different components within the plant is a feasible RIM strategy. The selection of a specific type of component or component material informs component reliability values. Two different approaches for component selection may be used to achieve the same system-level long-term reliability goals:

1) Use expensive components (highly-reliable with degradation-resistant material) to ensure adequate component performance over the long lifespan

2) Use cheaper components and/or materials and replace them multiple times during the same lifespan

A combination of design strategies and performance monitoring strategies may provide optimal solutions for meeting the long-term plant performance goals which can be accomplished by expanding the capabilities of the RIM framework.

4.2. Expansion of RIM Framework to Larger Context

In this case, the RCCS RIM strategies selection is rather a simple problem given that this system essentially has only two components of the same type (standing and connecting pipes), the same NDE and OLLD strategies are applied to all the components in the group (i.e., each standing pipe is assumed to have the same RIM strategy), and operational environment is simple (i.e., atmospheric pressure, low temperatures). The problem will become much more complex for a different system and when it needs to be solved for the entire plant vs a single system. A comparison of RIM program development cases for a simple and more complex system is presented in Table 1.

Table 1. Simple vs Complex System RIM Strategies Selection

Inputs	RCCS System Case Study	More Complex System
Number of components	Two component groups, same component types – all RCCS pipes are grouped into 1) standing pipes or 2) connecting pipes	Many more than two with different component types: e.g., pipes, valves, pumps, heat exchangers, etc.
NDE / OLLD options	Only 2 NDE and 2 OLLD options with simplified assumptions for a POD and cost The same option is applied for all the components (pipes) in the group	Multiple options, each associated with POD and costs estimates, each includes uncertainties A different strategy and different frequency can be applied for each component or a group of components
Operating Environment	Simple (i.e., atmospheric pressure, low temperature) Same for the entire system	Complex (e.g., high temperature, pressure, vibration, etc.) Varying for different components in the system
Degradation Mechanisms	RCCS has no applicable degradation mechanisms; random failure is postulated instead	Multiple degradation mechanisms possible Different mechanisms could be applicable for different system components
Lifespan	Same for all system components	Possibility of variable lifespan for different components in the system (e.g., 100+ years for not accessible / high safety significant components, 20 years for the rest of the system)
Reliability Target	A single reliability target	Hazard-dependent (e.g., internal event, seismic) From nuclear safety risk perspective From investment protection perspective

As mentioned earlier, 9801 available RIM strategies were identified for the very simple RCCS case study. Given considerations presented in Table 1, the RIM strategies optimization problem for a more complex system will have many more degrees of freedom which makes the problem impossible to solve without using a specially-developed framework.

5. CONCLUSION

This paper describes the research focused on development of strategies and approaches supporting establishment of a Reliability and Integrity Management Program for power plants based on advanced nuclear technologies. This research is of a paramount importance because it is directly related to regulatory licensing of advanced reactors and expedited deployment of the new nuclear technologies.

The R&D conducted thus far developed and demonstrated an initial framework that can support RIM program development for any advanced reactor. The use of this framework by advanced reactor developers is extremely beneficial because it allows to:

- Optimize the selection of strategies for plant performance monitoring that ensure both safety and economic goals are met
- Expedites regulatory licensing review process since the framework is built based on the regulatory-approved approaches

Additional research and development are warranted to expand the capabilities of the framework to support the entire RIM program development not only on a system level, but most importantly on the plant level.

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