Data Analytics for Reliability and Integrity Management

D. Mandelli[1, *], C. Otani[1], T. Anselmi[1], S. Lawrence[1], C. Smith[1], E. Ryan[1]

[1] Idaho National Laboratory, Idaho Falls, ID

[leave space for DOI, which will be inserted by ANS]

ABSTRACT

New reactor designs are focused on risk-informed processes to support all stages of development (design, licensing, operation, and retirement). Some of these processes are well-known since they are used for light-water reactors; however, the safety classification of systems, structures, and components (SSCs), development of performance requirements, and application of special treatments are unfamiliar to light-water reactors. More specifically, developing and monitoring performance requirements are a completely new problem. An industry initiative led by the American Society of Mechanical Engineers has been in development for a few years—requirements for a reliability and integrity management (RIM) program for nuclear power plants. The objective is to define, evaluate, and implement strategies to ensure that SSC performance requirements are defined, achieved, and maintained throughout the plant lifetime. This paper provides an overview of the data analytics methods designed to support the RIM program for advanced reactors, and it targets two research directions: SSC reliability target allocations and RIM strategy identification and evaluation. These methods are applied to specific case studies. These analyses present various possibilities and options for meeting RIM program requirements, including considerations of a tradeoff between reliability and economics and design option optimization.

Keywords: Reliability management, decision-making, optimization

1. INTRODUCTION

Every nuclear power plant (NPP) in the United States and around the world is obligated to maintain high safety levels 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 the 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" [1]. 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" [2] as one acceptable method for non-light-water reactor (non-LWR) designers for selecting licensing basis events (LBEs); classification and special treatments of structures, systems, and components (SSCs); and assessment of defense in depth (DID). All of these activities are fundamental to the safe design of non-LWRs.

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

* Corresponding author only: diego.mandelli@inl.gov

- Systematic definition categorization and evaluation of event sequences for selecting LBEs, which include anticipated operational occurrences, design basis events, design basis accidents, and beyond design basis events
- Systematic safety classification of SSCs, development of performance requirements, and application of special treatments
- Systematic adherence to guidelines for evaluating DID adequacy.

Some of the above processes are well-known since they are used for LWR licensing, such as the systematic definition and evaluation of event sequences and DID. However, other topics such as the risk-informed SSC safety classification and development of performance requirements are familiar to LWRs. More specifically, developing and monitoring performance requirements is a completely new problem that does not exist in the LWR domain. The 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 toward deterministic methods and only recently started shifting toward risk-informed approaches and to a lesser degree toward performance-based approaches. Another industry initiative led by the American Society of Mechanical Engineers (ASME) has been in development for a few years—defining requirements for a reliability and integrity management (RIM) program for NPPs [3]. 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 technology-inclusive, risk-informed, and performance-based approach described in RG 1.233 and, given it was endorsed by the NRC in RG 1.246 [4], can serve as an acceptable and satisfactory approach to addressing the systematic safety classification of SSCs, development of performance requirements, and application of special treatments.

The NRC endorsement adds urgency for developers of new reactor designs to understand how ASME Section XI, Division 2 should be implemented. ASME Section XI, Division 2 provides requirements for creating the RIM program for any type of reactor, even though RG 1.246 endorses its use for non-LWRs. The RIM program can be beneficial to the industry by reducing implementation costs and providing consistency in implementation for users. However, there is no industry experience to draw from and limited guidance on meeting the requirements for developing the risk-informed RIM program.

Therefore, the Regulatory Framework Modernization Program within the Regulatory Development supporting the Department of Energy's Office of Nuclear Energy initiated a project to develop guidance based on ASME Section XI, Division 2 requirements for non-LWR developers through the establishment of the risk-informed RIM program. This paper covers a limited scope focused on two key steps: SSC reliability target allocations and the identification and evaluation of RIM strategies.

2. RIM PROGRAM DEVELOPMENT

The development of the RIM program requires determining *what* to monitor and examine to meet the end-goal plant operational requirements (i.e., safety, investment protection, and licensing), and *how* to monitor and examine the selected "what". As the result of RIM program implementation, we developed a RIM strategy to monitor system performance at each level, either the complete system or multiple subsystems, and for each SSC. Each task in the RIM program development is broad and complex; however, some tasks are more straightforward because they are similar to processes implemented by existing NPPs. For example, the damage mechanism assessment is a well-known process within the industry, such as during risk-informed in-service inspection and license renewal activities. While damage phenomena and mechanisms may be different between advanced reactors and LWRs, their assessments follow similar steps. Other tasks are more complicated because they are newly introduced in ASME Section XI, Division 2 or use methodologies and approaches that are novel to the industry.

3. RELIABILITY TARGET ALLOCATION

The SSC reliability target allocation process involves considering multiple aspects largely grouped into two categories:

- Regulatory limits on the risks, frequencies, and radiological consequences of LBEs determined based on multiple considerations, including deterministic analyses and evaluations, insights obtained from the plant probabilistic risk assessment (PRA), and DID aspects.
- Requirements for plant availability and investment protection defined by the limits on the risks related to the loss of production or assets determined by the plant reliability, availability, and investment protection PRA.

Selecting reliability targets establishes a benchmark for evaluating system performance. As such, the initial phase of the RIM program develops reliability targets, 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:

- *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*. This step defines the accident scenarios that could lead to a release associated with source terms identified in Step 1. The accident parameters include SSC failure modes and associated failure probabilities that may lead to an accident. This step results in determining the frequency of each possible accident scenario.
- *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 a high redundancy of mechanical systems (e.g., three train system) while another design may use the high reliability of the primary system (e.g., passive cooling system) supported by a backup system for DID. The system-level reliability targets are assigned in a way that the plant-level reliability targets remain in the designated LBE category—anticipated operational occurrences, design basis events, and beyond design basis events—including uncertainty considerations.
- *Step 4: Component-level reliability targets*. This is the step where failure modes and 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 evaluated 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 in how much of a risk increase (or reliability decrease) each SSC can afford before the 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.

4. EXAMPLE OF RIM STRATEGIES EVALUATION

The initial framework was developed using publicly available information using a single, simple system to demonstrate RIM strategy selection. The system used for the initial framework demonstration is a reactor cavity cooling system (RCCS) for a high-temperature gas reactor. The pebble-bed modular reactor RCCS was used as the initial design. The pilot study performed for the pebble-bed modular reactor passive component reliability and integrity management was used as the starting point for the initial setup of the RIM framework in this paper [5],[6].

The RCCS primary function is to remove thermal radiation from the reactor vessel and release this heat to the atmosphere. This pilot study used a water-cooled RCCS design. RCCS failure does not pose nuclear safety concerns, but DID relies on RCCS, so it should remain operable at all times. In addition, RCCS failure could cause reactor cavity flooding, an undesirable consequence in terms of availability and investment protection. A simplified RCCS design schematic used in the initial framework is presented in Figure 1. Water flowing through the standpipes around the reactor vessel walls removes heat. This water is normally supplied from a water source or outdoor tanks when the normal source is not available via connecting pipes. Since the system failure mode of primary concern is a pipe or weld failure that would flood the reactor cavity, only a portion of the RCCS is here considered, which includes standing pipes and a fraction of connecting pipes. Therefore, there are only two groups of components, standing and connecting pipes, modeled in the RCCS RIM framework.

For the scope of this work, RIM strategy is the combination of nondestructive examination (NDE) and online leak detection (OLLD) strategies. The RCCS RIM framework considers three NDE options: phased array (with an assumed simplified probability of detection [POD] of 0.5), eddy current + ultrasonic (with an assumed POD of 0.9), and “do nothing” (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. The framework considers three OLLD options: visual examination (with an assumed POD of 0.5), imaging spectra (with an assumed POD of 0.9), and “do nothing” (no OLLD at all). The considered frequencies for the OLLD options are 1.5, 3, 4.5, and 6 years.

Although developing a RIM strategy focuses on meeting a desired reliability measure, costs can be considered when selecting from strategies that achieve the desired reliability since operations and maintenance costs become a very important aspect of a successful long-term facility operation. Therefore, cost considerations are included in this evaluation. The cost portion of the RIM model considers both fixed and variable costs. Fixed costs include personnel training and equipment costs. Variable costs are estimates for each inspection, including 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 uses a rate of $100 per hour to perform typical inspection activities. Cost multipliers differentiate the cost impacts of NDE and OLLD activities.

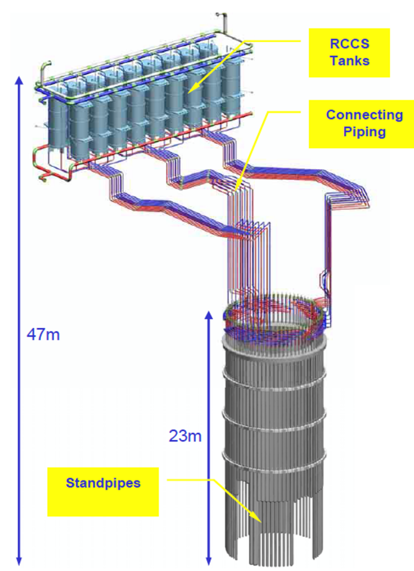

Figure 1. Schematic representation of the RCCS system.

The RCCS RIM model uses a Markov model for predicting the effect from various inspection strategies on the RCCS piping reliability, a method based on the research described in [6]. Here an RCCS RIM strategy is the combination of the RIM strategies associated with the connecting pipes and standing pipes. For each pipe group, a RIM strategy is a combination of NDE and OLLD (i.e., leak) strategies. Given the chosen

NDE and OLLD types, the total number of possible RIM strategies is 9,801 [$(11\cdot9)^2 = 9801$]. Choosing optimal RIM strategies occurs in a multi-objective optimization fashion where the objectives that need to be minimized are RCCS flooding frequency and surveillance costs. 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 2. All possible RCCS RIM options are shown in blue while the optimal ones (i.e., the Pareto frontier) are shown in red. Figure 2 shows, in particular, two relevant cases: one where no NDE and OLLD are performed (which results in a low cost and high flooding frequency) and a second one where the best NDE and OLLD activities are performed very frequently (which results in high costs and a low flooding frequency). Note that the Pareto frontier is characterized by a rapid increase in costs that occur as one passes the knee of the curve at about 2.5E-4, since past 2.5E-4, no NDE is chosen for both pipe sets (only OLLD). If a system reliability target is provided (highlighted in green), the RCCS RIM strategy on the left of such a target should be chosen.

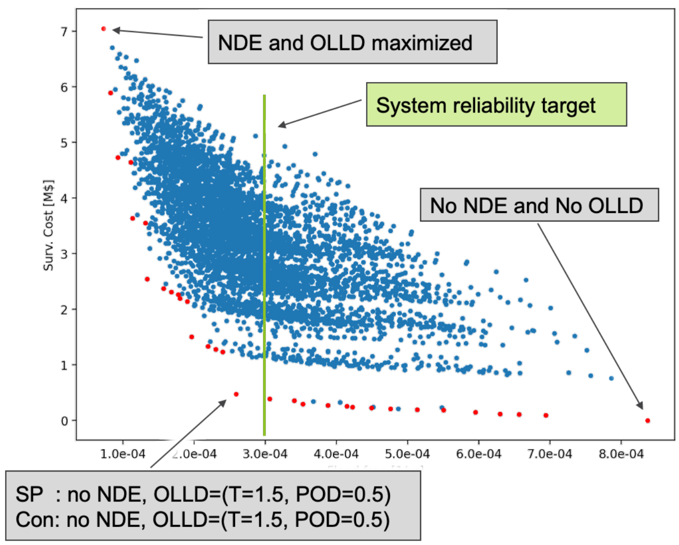

Figure 2. RCCS multi-objective optimization to evaluate optimal RIM strategies.

5. SYSTEM RELAIBILITY TARGET ALLOCATION: SYSTEM-CENTRIC APPROACH

The example provided In Section 4 gave the system reliability target. One of the RIM program goals is to determine such a target based on regulatory constraints. With that in mind, note that:

- The degrees of freedom are the asset options available
- The objective function to be minimized is the sum of all option costs for considered assets

We employed an optimization formulation in a single-objective form:

$$\min_{\boldsymbol{opt}} \quad cost(\boldsymbol{opt})$$
$$s.t. \quad f_m^{RR}(\boldsymbol{opt}) \leq f_{reg}^{RR}$$

where:

- $\boldsymbol{opt} = [opt_1, \dots, opt_S]$ represents the "decision space" and consists of the set of options of the considered S assets
- $cost(\boldsymbol{opt})$ represents the cost of a generic option $\boldsymbol{opt}$, and in its most simple form (as in this work), is the sum of the costs associated with each asset option: $cost(\boldsymbol{opt}) = \sum_{s=1}^{S} cost(opt_s)$

- $f_m^{RR}(\boldsymbol{opt})$ represents the frequency of radioactive release for the considered IE_m, which is upper bounded as dictated by the regulatory limit (e.g., limit identified by the LMP approach (NEI, 2019)).

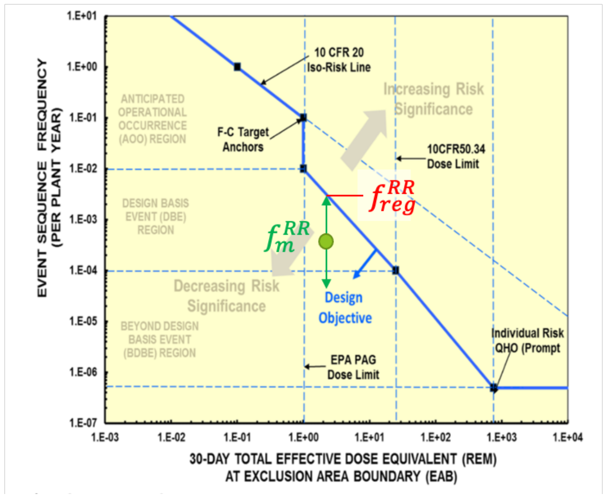

Figure 3. Single-objective optimization problem for a single initiating event.

Figure 3 presents a graphical representation of a single-objective optimization problem for a single initiating event. In this case, the regulatory limit is the constraint for the optimization function. The reliability target is not a single value; it is a range of values that satisfy predetermined requirements. From the regulatory standpoint of view, it is desirable to set reliability targets in such a way that the event sequence frequency, represented by a point on the frequency-consequence curve (i.e., the green circle on Figure 3), is as low as possible on the y axis (i.e., the event sequence frequency is minimized). However, from the cost perspective, it is more desirable for the point on frequency-consequence curve to be as high as allowable by regulatory limits since system reliability is proportional to system procurement costs.

Our study considered a generic reactor plant characterized by the following constituent elements:

1. The plant consists of N systems (e.g., AC power system, core injection system) where each system is designed to support one or more functions. A system is not an isolated entity but either supports or is supported by other system(s).
2. The plant is comprised of S assets (e.g., centrifugal pumps, motor-operated valves) designed to support system functions. Each asset is modeled from a reliability standpoint by one or more basic events (BEs), where R represents the number of the complete set of BEs.
3. At the design phase, each asset can be chosen from a set of options; without losing generality, we considered two options for a generic asset:
   a. Option 1: high-quality and highly reliable asset (high procurement cost)
   b. Option 2: lower quality and less reliable asset (low procurement cost).
4. A set of M initiating events (IEs) are considered IE_m $(m = 1, \dots, M)$ where the frequency f_m of occurrence of each IE_m is known. A PRA model $\mathbb{R}_m$ is available for each IE. $\mathbb{R}_m$ determines for IE_m the frequency f_m of an undesired event called an event sequence (e.g., frequency f_m^{CD} of core damage or frequency f_m^{RR} of radioactive release). The $\mathbb{R}_m$ consists of a set of fault trees and event trees. For each IE_m it is possible to calculate $f_m = \mathbb{R}_m(f_m, P_1, \dots, P_r, \dots, P_R)$ where P_r indicates the probability of each basic event BE_r $(r = 1, \dots, R)$.

We determined system reliability targets using a system-centric approach structured in two steps, each involving an optimization process. This approach graphically summarized in Figure 4 is:

1. System optimization step—determine Pareto frontier for each system S_n (see RCCS RIM analysis in Section 4)

- *Model employed*: set of minimal cut sets (MCSs) from system fault tree model
    - Here we considered the supporting systems to be perfectly reliable, which is needed to separate the system of interest S_n from the rest of the supporting systems
- *Data required*: Asset options (BEs probability, cost)
- *Data generated*: Optimal set of asset options at the system level (i.e., Pareto frontier as performed in Section 4 for the RCCS system)

2. Event sequence optimization step
    - *Degrees of freedom*: Set of options for each system (obtained in Step 1)
    - *Model employed*: Set of MCSs for the considered IE
    - *Objective function*: Minimize plant costs and maintain plant reliability regulatory constraints
    - *Data generated*: Optimal Pareto option for each system.

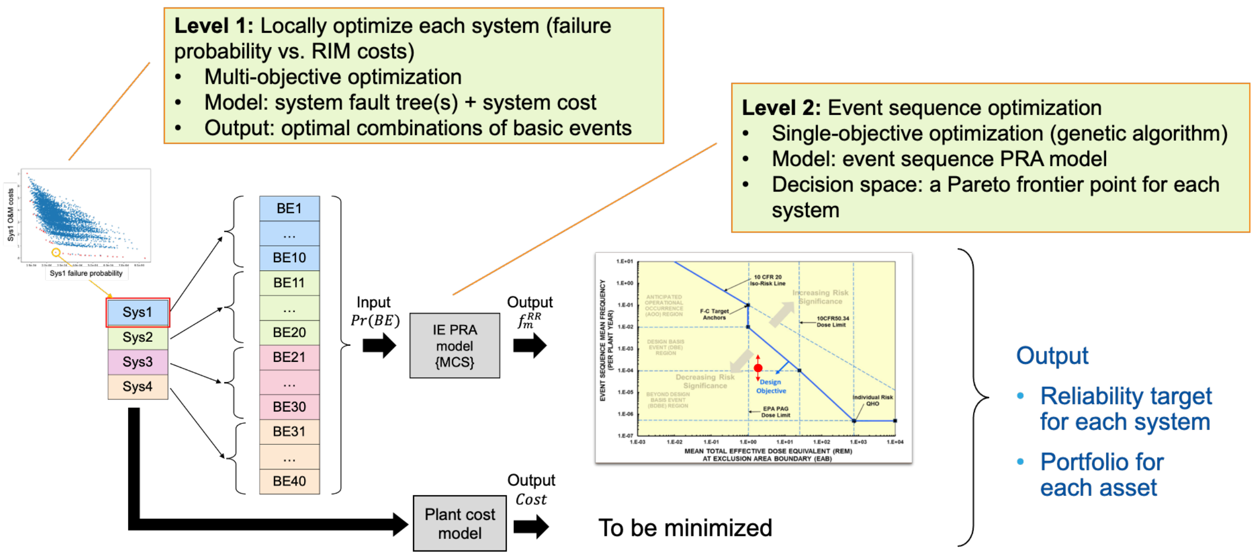

Figure 4. Graphic representation of system-centric optimization approach for a system of four subsystems and 40 BEs.

Note:

- The Pareto frontiers obtained in Step 1 are used primarily to filter out nonoptimal system configurations and keep the problem tractable by making problem complexity smaller (dimensionality wise).
- The decision space is reduced since the dimensionality of the problem is dictated by the considered number of systems rather than then number of assets.
- The number of options for each dimension is larger and equal to the number of points that compose the system Pareto frontier.
- The model employed in Step 2 is the full PRA model for the considered IE.

6. EXAMPLE OF SYSTEM RELIABILITY TARGET ALLOCATION

To test and show the proposed approach, we have selected a well-known IE for existing LWR plants: a large-break loss-of-coolant accident (LLOCA) scenario. We employed a publicly available pressurized water reactor (PWR) PRA model[1]. The LLOCA PRA model is composed of both a single and multiple fault trees. The systems shown in Table 1 are credited for mitigating a LLOCA event.

More observations about the LLOCA PWR PRA model are:

- We identified 92 assets from the 10 systems listed in Table 1. They represent the decision space of the reliability target allocation example problem, and, hence, it is required to determine the optimal configuration of reliability targets for these 92 assets.
- The number of BEs is slightly larger (i.e., 118) than the number of assets since more than one BE is associated with some assets. These correlations between assets and BEs need to be captured.
- The association between assets and the system is typically well defined (i.e., an asset is associated with a unique system). However, it is common for a system to support multiple functions in the PRA model. In such cases, multiple assets are associated with multiple systems.
- We used a regulatory constraint set to $f_{reg}^{RR} = 6.23\text{E} - 9 \text{ yr}^{-1}$.

Table 1. List of systems identified in the LLOCA PRA model.

System ID	Description
ACC	Accumulator tanks
ACP-480	480 V AC power system
ACP-4160	4160 V AC power system
CCW	Component cooling water
DCP-125	125 V DC power
EPS-SWS	Emergency power system service water system
LPI	Low-pressure injection system
LPR	Low-pressure recirculation system
RWST	Refueling water storage tank
SWS-TRNA	Service water system train A

We created a simulation model of the PWR LLOCA system that consisted of the following three sub-models (see Figure 5):

- *Option model*: This model receives the selected option for each asset (or for each system) as an input, and it generates the corresponding BE probability and asset cost values. We created this model ad hoc for this specific application.
- *Reliability model*: This model contains the LLOCA MCSs (about 20,000) and determines the frequency of the LLOCA sequence provided BE probability values. For the specific PWR LLOCA test case, evaluating the generated set of MCSs takes about 1.6 seconds.
- *Cost model*: This model simply sums up all the cost values for the considered assets. Here we have only considered procurement and installation costs. Note that, depending on the use case being considered, this model can be more complex and include several economic aspects that can be projected over the planned lifetime of the plant, such as maintenance, monitoring, and surveillance costs.

[1] https://doi.org/10.2172/1804754

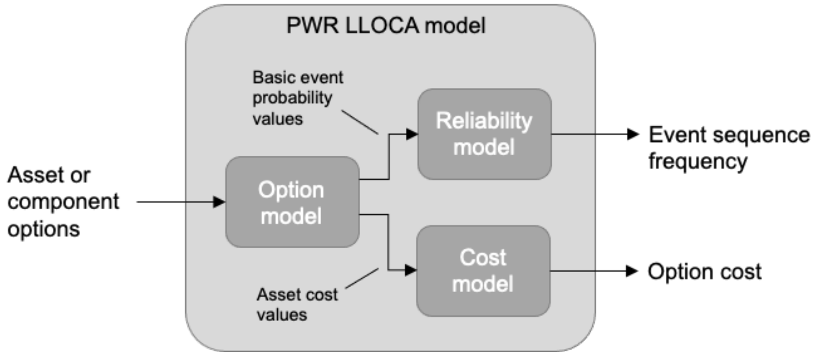

Figure 5. Graphical representation of the PWR LLOCA model employed to optimize the RIM strategy.

Table 2. List of Pareto frontier points for the system identified in the LLOCA PRA model.

System ID	# of Pareto frontier points
ACC	5
ACP-480	8
ACP-4160	23
CCW	17
DCP-125	5
EPS-SWS	9
LPI	13
LPR	6
RWST	4
SWS-TRNA	6

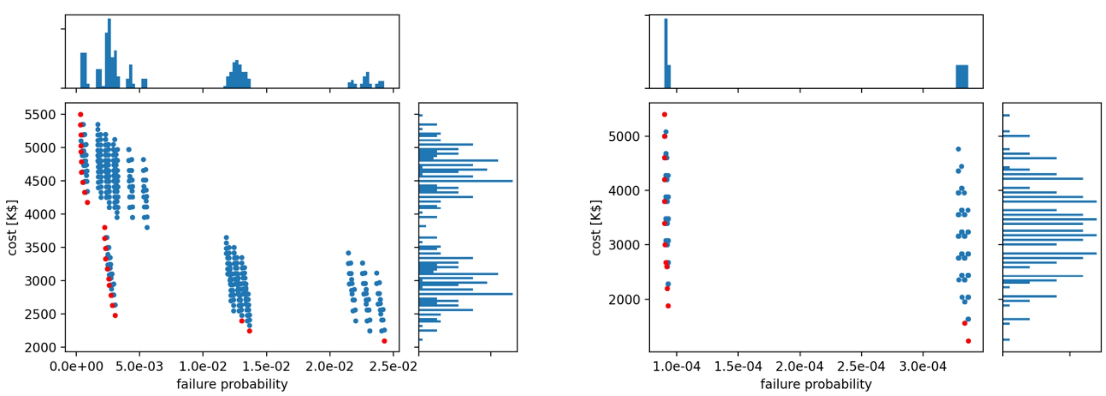

Figure 6. Complete set of options (blue points) and Pareto frontier options (red points) for the ACP4160 (left) and LPI (right) systems.

Assuming that only two options are available for each component (i.e., lower and higher reliability), there are $2^{92} = 4.95 \times 10^{27}$ possible combinations. Even if the same option is assigned to identical assets belonging to different trains, the number of combinations drops to $2^{42} = 4.40 \times 10^{12}$ possible combinations. Assuming evaluating the PWR LLOCA model for each combinations takes 3.5 seconds, the evaluation of all combinations would take 488,114 years. Obviously, this option for reliability target allocation is not feasible, and we considered alternatives.

For the scope of this paper, we have solved the RIM optimization problem using the genetic algorithm. The system reliability target allocation required two optimization steps (see Section 5). The first step (system optimization) required a multi-objective optimization analysis for all considered systems. In this respect, Table 2 lists the number of points that are part of the Pareto frontier for all considered systems. Note that in this case the complete number of system combinations obtained by multiplying all numbers listed in Table 2 is $1.317 \cdot 10^9$ (which is three orders of magnitude lower than the number of asset combinations). However, such a number is still high; assuming evaluating the PWR LLOCA model for each combination takes 3.5 seconds, the evaluation of all system combinations would now take 146 years (rather than 488,114 years). A graphical representation of the Pareto frontiers obtained for the ACP-4160 and LPI systems is shown in Figure 6. The second step (event sequence optimization) consisted of a single-objective optimization on the 10-dimensional space using genetic algorithms where each dimension is represented by a Pareto frontier point for each considered system. From this analysis, the sample that satisfies regulatory constraints ($f_m^{RR}(\boldsymbol{opt}) \leq f_{reg}^{RR}$) and minimizes costs had a value of $cost(\boldsymbol{opt}) = 24{,}670\, K\$$ and $f_m^{RR}(\boldsymbol{opt}) = 5.53\, E - 9\ 1/yr$.

7. CONCLUSIONS

This report describes research focused on developing the technical framework and implementation strategies supporting establishing a RIM program for advanced nuclear reactors. This research is of paramount importance because it is directly related to the regulatory licensing of advanced reactors and expedited deployment of new nuclear technologies. The research and development conducted thus far developed and demonstrated an initial technical framework that can support RIM program development for any advanced reactor. Using this framework is extremely beneficial because it allows advanced reactor developers to:

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

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

REFERENCES

[1] NRC, "Regulatory Guide 1.233 Revision 0: 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," U.S. Nuclear Regulatory Commission, ML20091L698, 2020.

[2] NEI, "Risk-Informed Performance-Based Technology Inclusive Guidance for Non-Light Water Reactor Licensing Basis Development," Nuclear Energy Institute, Technical Report 18-04, 2019.

[3] ASME Section XI, Division 2, "Requirements for Reliability and Integrity Management (RIM) Programs for Nuclear Power Plants," 2019 ASME Boiler & Pressure Vessel Code, Section XI: Rules for Inservice Inspection of Nuclear Power Plant Components, Division 2, 2019.

[4] NRC RG 1.246, "Acceptability of ASME Code, Section XI, Division 2, Requirements for Reliability and Integrity Management (RIM) Programs for NPPs, for non-LWRs," U.S. Nuclear Regulatory Commission, October 2022.

[5] K. Fleming, S. Gosselin and R. Gamble, "PBMR Passive Component Reliability Integrity Management (RIM) Pilot Study," *Technology Insights*, 2007.

[6] K. N. Fleming, "Markov models for evaluating risk-informed in-service inspection strategies for nuclear power plant piping systems," *Reliability Engineering and System Safety,* vol. 83, pp. 27-45, 2004.