THE IMPACT OF EXTERNAL HAZARDS AND FLEX CREDIT IN THE APPLICATION OF LICENSING MODERNIZATION PROJECT FOR OPERATING REACTORS

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Abstract: As part of the Nuclear Regulatory Commission's (NRC's) effort to provide resources to longer-term, forward looking research projects with potential regulatory benefits, a future focused research (FFR) project was established to study the implementation of the Licensing Modernization Project (LMP) methodology for the operating reactors. This research effort used the LMP methodology and applied the NRC's Level 3 probabilistic risk assessment (PRA) model results to gain feasibility insights. The initial phase of this effort used results from a limited scope of the NRC's level 3 PRA model to explore key risk-insights of the licensing basis for reactors licensed under Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50. The next phase of this effort addressed in this paper uses the expanded results from the NRC's level 3 PRA model that includes model enhancements.

This paper compares the results derived from the level 1, level 2, and level 3 PRA models for internal events and internal floods with the results that include external events. Moreover, the paper uses this comparison to gain insights on the impact of modelling external hazards, identify implementation challenges, and explore the feasibility of using results that consider the impact of external hazards in the LMP framework. These PRA results are used in the context of the frequency consequence (F-C) curve to both gain experience with the overall LMP methodology's risk-informed performance-based guidance and to identify key risk-insights on operating reactor technology. Furthermore, these insights provide an example of a "safety case" for operating plants which include discussions on the risk-important plant events, potential risk ranking of systems, structures, and components (SSCs), and a risk-informed defense-in-depth evaluation of the plant. Insights may also support future studies to highlight portions of Part 50 that are the best candidates for further risk-informed considerations.

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1. INTRODUCTION

The NRC's future focused research (FFR) program was approved by the Commission in 2020 to focus on longer-term research and development (R&D) needs. The FFR program is intended to be a limited resource effort that is streamlined to support transformation and the vision of becoming a modern, risk-informed regulator. The approved FFR projects are used to identify, align, and close technical gaps ahead of regulatory needs and possibly be the foundation for extended R&D efforts outside the FFR program. The FFR program is also used to attract and retain top talent and build technical capabilities.

The Licensing Modernization Project (LMP) for operating reactors project was approved in 2020 and had several overall goals, including gaining risk-insights on operating reactor technology, exploring the feasibility of the LMP methodology, and providing NRC staff with valuable technical experience. Phase 1 of this project was limited in scope and used the LMP methodology, described in SECY-19-0117 and described in more detail in NEI 18-04 and Regulatory Guide (RG) 1.233, to gain risk-insights on operating reactor technology. This risk-informed and performance-based guidance provided a framework to develop insights into key parts of the licensing basis for reactors licensed under 10CFR Part 50 and can provide areas for resource considerations. The NRC's level 3 probabilistic risk assessment (L3PRA) model results used for phase 1 was limited to internal events and internal flooding.

For phase 2 of this project, the enhanced NRC's L3PRA results were used. This enhanced L3PRA model was expanded to include external hazards (i.e., internal fires, seismic, and high winds), credit for FLEX equipment, along with other model enhancements. This paper will share results from both phase 1 and phase 2. Along with these insights, this project explores the feasibility of using the LMP methodology and identifies possible efficiencies for future reactor designers and applicants.

2. BACKGROUND

This research uses the NRC's past and ongoing accident analysis work to support both the understanding and application of the LMP methodology and the work on modeling severe accidents in the NRC's L3PRA project. Specifically, this research relies heavily on the extensive work done by NRC staff and external stakeholders to develop and endorse the LMP methodology. Below is a brief background on the NRC's historic licensing processes, the NRC's previous severe accident research projects, the LMP methodology, and the NRC's L3PRA project.

2.1 10 CFR Part 50 Licensing

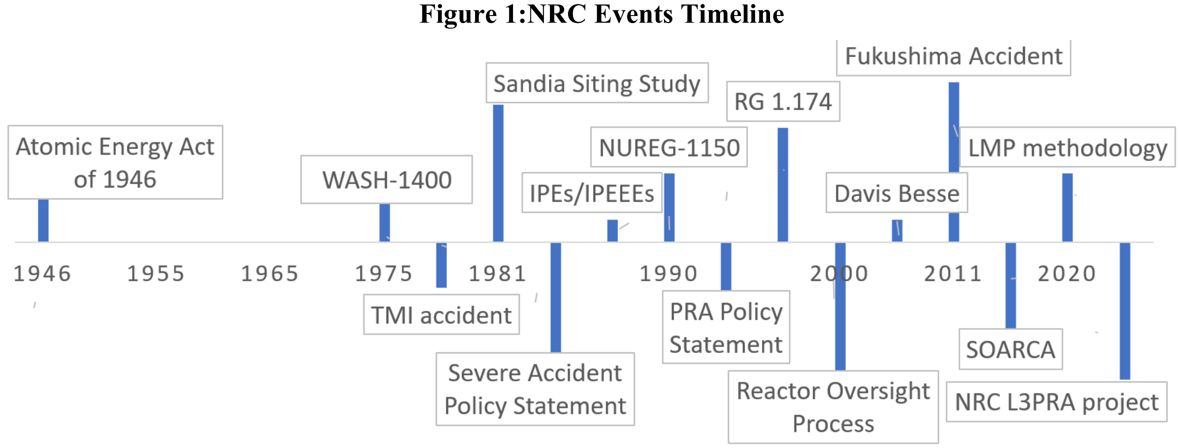
All currently licensed and operating commercial nuclear power plants in the U.S. have been licensed under 10 CFR Part 50. This licensing process is a two-step process that includes first obtaining a construction permit to build the plant and then an operating license to operate the plant. In 1989 the NRC established an alternative to the two-step process in 10 CFR Part 52, which includes a combined license and the ability to certify a plant design.

Many of the NRC's regulations are based on deterministic and prescriptive requirements. The operating reactor designs relied heavily on a deterministic approach for both designing and licensing. Appendix A to Part 50 includes the General Design Criteria which establish minimum requirements for water-cooled nuclear power plants and was used by the current operating reactors. The principal design criteria establish the necessary design, fabrication, construction, testing, and performance requirements for structures, systems, and components (SSCs) important to safety; that is, SSCs that provide reasonable assurance that the facility can be operated without undue risk to the health and safety of the public.

2.2 NRC's Severe Accident Research

The NRC and its predecessor, the Atomic Energy Commission (AEC), have consistently applied analytical tools to assess severe accidents at U.S. commercial nuclear power plants and how these accidents might affect nearby populations and the environment. Below in Figure 1 are NRC major events and analysis that have helped shape the current regulatory framework.

Figure 1:NRC Events Timeline



The AEC started the Reactor Safety Study, which the NRC completed in 1975 as the WASH-1400 report. This study used probabilistic risk assessment (PRA) techniques to study reactor accidents and their estimated consequences and ultimately concluded that the risk from a reactor accident is low relative to other man-made and naturally occurring risks [1, 2]. The Three Mile Island (TMI) reactor accident in 1979 changed the NRC's approach to both severe accident research and to using PRA to support regulatory decisions [3]. The NRC has subsequently analyzed reactor accidents in several research projects. This includes the publication of NUREG-1150, "Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants," which assessed the risks from severe accidents at five U.S. nuclear power plants [5]. The NRC began the State-of-the-Art Reactor Consequence Analyses (SOARCA) project in 2007 to continue the process of enhancing the realism of estimates for public health consequences due to nuclear power plant accidents. SOARCA used three of the plants that were studied in NUREG-1150 (Surry, Peach Bottom, and Sequoyah) to analyze several scenarios, including an earthquake-induced loss of all electrical power known as a station blackout, along with uncertainty analyses [6, 7, 20]. The project combined up-to-date information about the plants with local population data and emergency preparedness plans.

2.3 LMP Methodology

The NRC has a long history of working with stakeholders on regulatory requirements/guidance for non-LWR designs. Some of these interactions started back in the 1980s and 1990s and have continued into the 2000s. The NRC staff provided the Commission with recommendations in SECY-03-0047, "Policy Issues Related to Licensing Non-Light-Water Reactor Designs," that are important to the methodology described in NEI 18-04 and RG1.233. These key licensing issues include selecting licensing basis events (LBEs), classifying SSCs, using probabilistic risk assessments, and providing appropriate defense-in-depth (DID) in non-LWR designs and programmatic controls [8]. The Commission approved the staff's recommendation to allow the use of risk insights to identify events, classify SSCs, and provide an alternative to the single-failure criterion for designing and licensing non-LWRs.

In 2008, the Commission issued its Policy Statement on the Regulation of Advanced Reactors, which included items to be considered in advanced nuclear power reactor designs [9]. The policy statement identifies attributes that could affect the review of a proposed advanced reactor design, including reliable and less complex shutdown heat removal systems; longer time constants before reaching safety system challenges; simplified safety systems that, where possible, reduce required operator actions; reduced potential for severe accidents; and considerations for safety and security requirements together in the design process.

In December 2007, the NRC staff published NUREG-1860, "Feasibility Study for a Risk-Informed and Performance-Based Regulatory Structure for Future Plant Licensing", which further explored the feasibility of developing a risk-informed and performance-based regulatory structure for the licensing of future nuclear power plants [10]. NUREG-1860 documents a "Framework" that provides an approach, scope and criteria that could be used to develop a set of requirements that would serve as an alternative to 10 CFR 50 for licensing future nuclear power plants. Appendix E of NUREG-1860 provides an example application of the probabilistic approach for a pressurized water reactor (PWR) plant. The NUREG-1860 appendix E frequency-consequence (F-C) target line can be seen in figure 2, with the LMP F-C target line for comparison. The NRC staff continued interactions with the Department of Energy (DOE), industry, and other stakeholders on policy issues centered on the Next Generation Nuclear Plant (NGNP) project and developed a series of white papers that further defined approaches for topics that were eventually addressed in NEI 18-04 and RG 1.233 [11].

The LMP, which was a cost-shared initiative led by Southern Company was coordinated with the NRC staff activities. The LMP developed a technology-inclusive, risk-informed, and performance-based methodology to support the design and licensing of non-LWRs. The LMP proposals built upon the accepted higher-level approaches outlined in SECY-03-0047 by refining the methodologies described in the NUREG-1860 and the NGNP white papers to reflect interactions with the NRC and feedback from industry [12].

The Commission approved the LMP methodology as described in SECY-19-0117, "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 [13]." The LMP methodology is a modern technology-inclusive, risk-informed, and performance-based (TI-RIPB) approach for non-LWR licensing basis development.

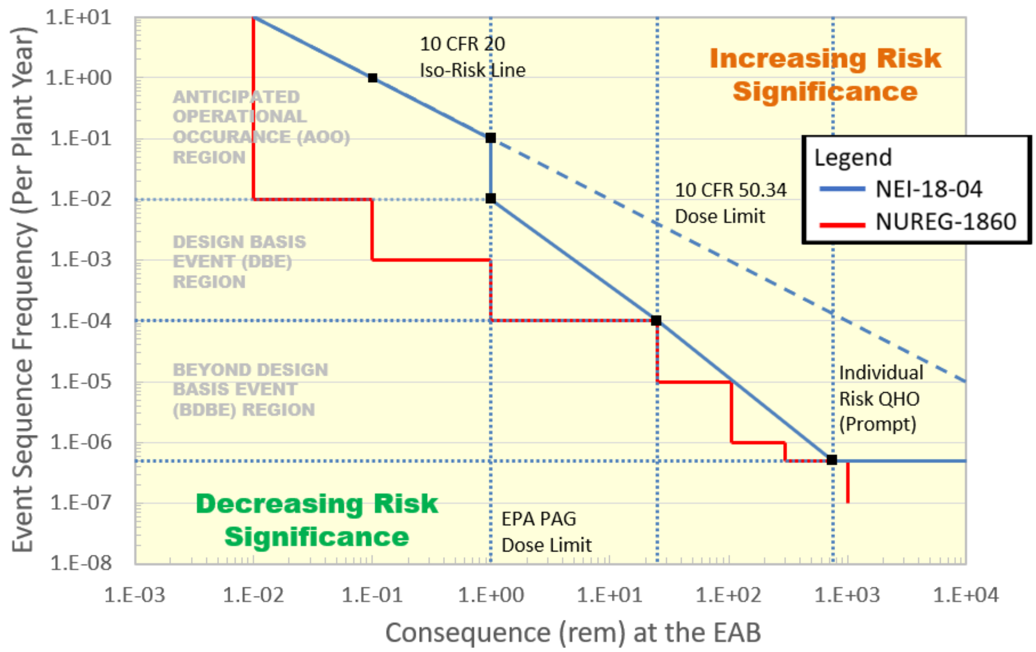
The overall objective of the guidance in NEI 18-04 and RG 1.233 is to describe a systematic and reproducible process for selecting LBEs, classifying SSCs, and assessing the adequacy of DID for non-LWR designs [14, 15]. The Commission's SRM for SECY-03-0047 previously addressed these three topics and the related topic of improving how the agency uses risk-informed and performance-based approaches in the Commission's PRA policy statement [16].

Since the LMP methodology is "technology-inclusive" it is not limited to applications on non-LWR technology and can be used to gain risk-insights on operating reactor technology. Although the F-C-curve requires a consistent consequence metric, e.g., a 30-day total effective dose equivalents (TEDE) at the exclusion area boundary (EAB), the reference values used are not necessarily computed in a consistent manner. The Environmental Protection Agency (EPA's) protective action guidelines (PAGs) are a 4-day TED that includes doses from deposited material, the 50.34 limit is a two-hour dose that does not include doses from deposited material, the Quantitative Health Objectives (QHOs) quantify health effects directly and do not use a dose but do (as usually computed) include credit for protective actions, etc. As noted in NUREG-1860 p. 6-6,

> "One advantage of this measure is that it is based on national and international regulatory practice, e.g., NRC regulations in 10 CFR 20 and 10 CFR 50, EPA (Environmental Protection Agency) protective action guidelines, IAEA guidelines and International Commission on Radiation Protection (ICRP) recommendations. However, the guidance that exists in terms of actual limits and how they are expressed is occasionally inconsistent since different values were developed at various times to serve different objectives."

The consequence metric used in NEI 18-04 is the 30-day TEDE at the EAB. The target anchors used in the LMP F-C curve (Figure 2) are different from the target line initially used in NUREG-1860. The LMP target points are 10 CFR 20 from the upper left to the 1E-01 rem dose point, from this point the EPA PAG dose limit of 1 rem is used for the second segment of Anticipated Operational Occurrence (AOO) ending in 1E-02 initiating event (IE) frequency/plant-year. The Design Basis Events (DBE) range of IEs from 1E-02 to 1E-04 /plant-year is covered using the EPA PAG dose limit to the 10 CFR 50.34 dose limit of 25 rem. The Beyond Design Basis Events (BDBE) region from 1E-04 to 5E-07 starts at the 10 CFR 50.34 dose limit and ends at a dose of 750 rem, which is used as a surrogate for prompt (early) health effects to reflect the QHO. The line does not go below the 5E-07 IE frequency/plant-year. The LMP document notes that lower frequency releases should be kept within the PRA and used to determine that there are no cliff edge effects and as evaluation for RIPB defense in depth (DID) analyses.

Figure 2: LMP Frequency - Consequence Chart



2.4 NRC's L3PRA Model

In 1995, the Commission established the NRC's policy for risk-informed regulation by issuing a PRA Policy Statement that stated the use of PRA technology should be increased in all regulatory matters to the extent supported by the state-of-the-art and in a manner that complements NRC's deterministic approach and traditional DID philosophy [16]. PRA is a structured, analytical process that provides both qualitative insights and quantitative estimates of risk by (1) identifying potential sequences that can challenge system operations and lead to an adverse event, (2) estimating the likelihood of these sequences, and (3) estimating the consequences associated with these sequences. PRA models can support decision-making by highlighting significant risk contributors and characterizing key sources of uncertainty. A full-scope comprehensive site Level 3 PRA that includes an assessment of accidents involving the reactor core as well as accidents involving other site radiological sources can provide valuable insights but can take significant resources to develop.

Using information from Level 3 PRAs performed in NUREG-1150, the staff determined that the reactor-specific risk metrics core damage frequency (CDF) and large early release frequency (LERF) can be used respectively as surrogates for the latent cancer risk and prompt fatality risk quantitative health objectives defined in the Commission's Safety Goal Policy Statement [4]. Therefore, instead of using resource intensive Level 3 PRAs, the staff compares the results from Level 1 and limited-scope Level 2 PRAs to subsidiary numerical objectives to support regulatory decision-making [17].

The NRC staff identified several reasons for proceeding with a new full-scope comprehensive site Level 3 PRA [18]. In the more than two decades that have passed since the NUREG-1150 Level 3 PRAs were performed, numerous technical advances have been made. Examples of such technical advances include

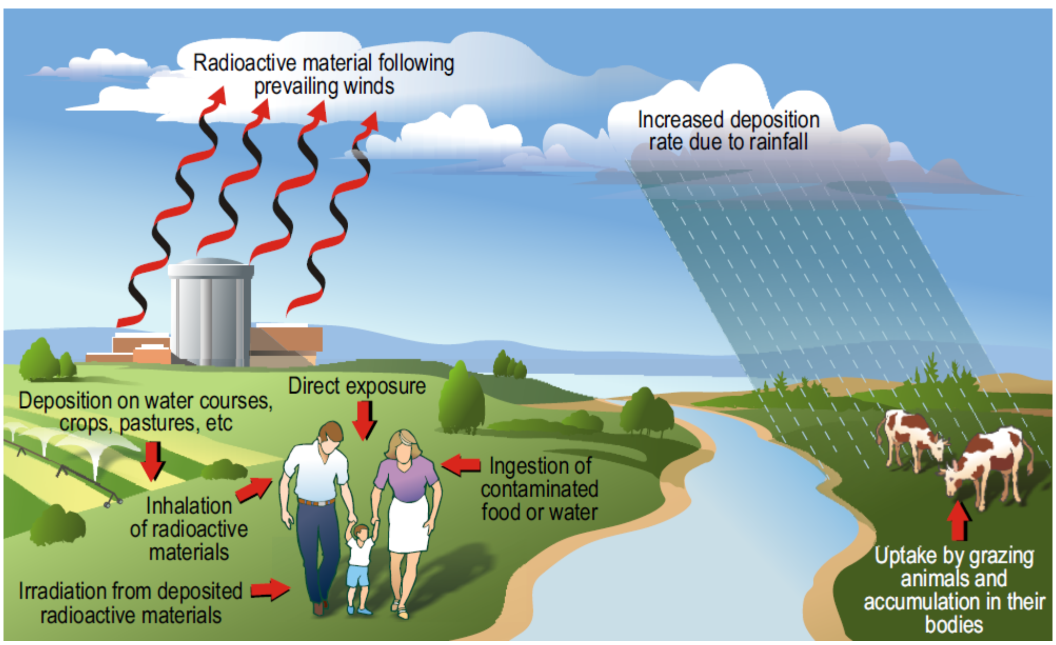
1. modifications to enhance nuclear power plant operational performance, safety, and security (e.g., development and implementation of risk-informed regulations; improved operational, maintenance, and training practices; implementation of severe accident management guidelines (SAMGs); and implementation of extensive damage mitigation guidelines (EDMGs) or B.5.b mitigation strategies;
2. significantly improved understanding and modeling of severe accident phenomena; and

3. advances in PRA technology (e.g., improved methods, models, analytical tools, and data through research and operating experience).

As described in SECY-11-0089, "Options for Proceeding with Future Level 3 Probabilistic Risk Assessment (PRA) Activities", the staff is conducting a full-scope site Level 3 PRA. While the scope of the Level 3 PRA study includes the assessment of risk associated with all internal events and external hazards the results presented in this paper include both the initial results for internal events and internal flooding and compares these to the all-hazard results, [17]. This NRC developed Level 3 PRA model represents existing light water reactor (LWR) technology. The thousands of accident sequences evaluated in the Level 1 analysis are condensed into a much smaller set of release categories that are used by the Level 3 model to estimate offsite consequences.

In the Level 3 portion of the analysis, the potential doses arising from each of these source terms are evaluated on a polar grid surrounding the site using the MELCOR Accident Consequence Code System (MACCS) software. The MACCS software allows the analysts to evaluate severe accidents at nuclear power plants. The MACCS code does this by modeling several different aspects of a severe accident, from the radioactive release, transport, and dispersion to the health effects to the public. Below in figure 3 is a basic depiction of what MACCS has the capability of evaluating.

Figure 3: MACCS Example Capabilities [19]

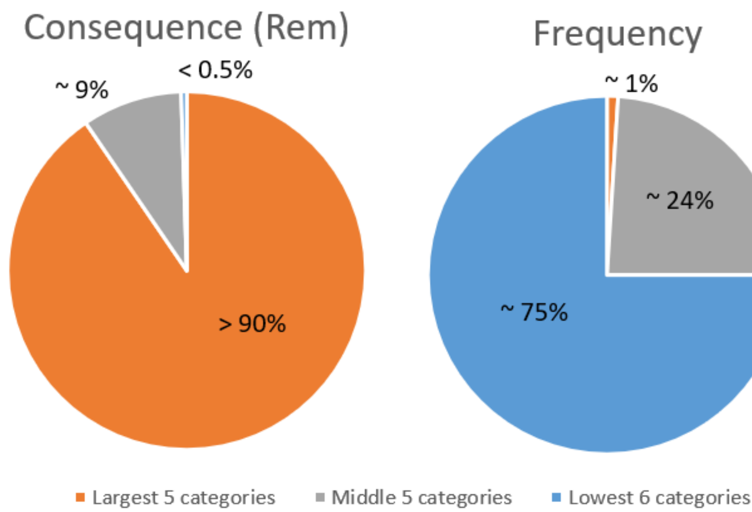


3. RESULTS

The results from the L3PRA analysis include both a variety of consequences (doses, health effects, etc.) from each release category as well as the individual frequencies of the different release categories. To use the LMP method F-C curve, the dose consequences at the exclusion area boundary are needed. As discussed above, there is a broad range of potential doses from these categories. The release categories have been grouped into three different classes based on the categories dose consequence to enable the release of the results. The five top release categories contribute over 90% of the overall dose, as can been seen in Figure 4. The lowest six release categories contribute less than 0.5% and are not visible in Figure 4.

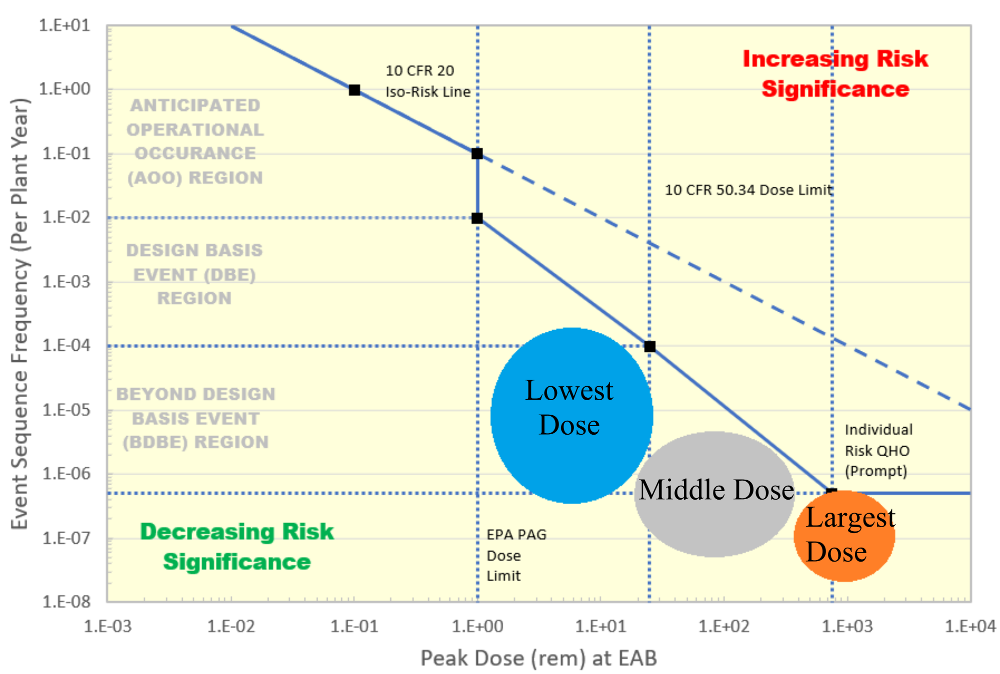
Figure 4 also shows the relative frequency comparison between the same grouped categories. The five release categories with the largest contribution to the consequence at the EAB has the smallest contribution to the overall frequency. Even though this group of release categories contributes more than 90% of the dose at the EAB, the frequencies of this group only contribute ~1% of the overall frequencies of accidents. The six release categories group that has the smallest contribution to the overall consequence at the EAB, has a ~ 75% contribution to the overall frequency of accidents.

Figure 4: Relative Consequence (Rem) and Frequency Comparison



Taking the 16 release category results from the initial NRC's L3PRA model results for internal events and internal flooding and plotting them on the LMP's F-C chart provides risk-insights that give a better perspective on the different release categories.

Figure 5: Phase I results F-C Chart with Release Category Bins



The five largest release categories dominate the other release categories in terms of magnitude of dose but only contribute minimally to the overall frequency of the accidents. The F-C plot in figure 5, provides a different perspective with the frequency of each category considered. Specifically, even though the lowest consequence release categories have significantly lower doses at the EAB, they also have frequencies that are magnitudes greater than the largest release categories. These five largest release categories by dose are contained within the orange circle and the six lowest dose release categories by dose are within the blue circle. The uncertainty for both the consequence and frequency metrics were not explicitly modeled in this project but the three different classes of release categories outlined in figure 5 are judged to encompass most of the uncertainty for each class. The LMP methodology requires the consideration of these uncertainties for each release category, which should be considered by reactor designers and applicants when using the LMP method.

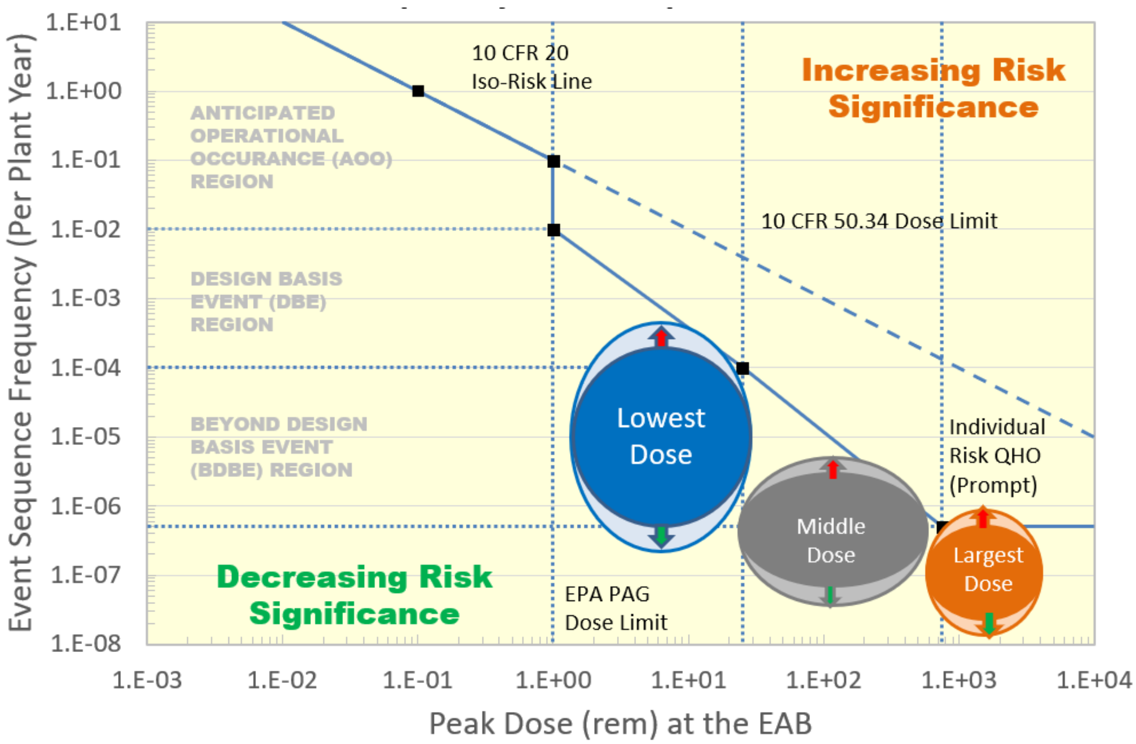
In phase 2 of this project, the frequencies associated with the enhanced NRC's L3PRA model were used. The source terms associated with the different release categories remained the same from phase 1 to phase 2, so there weren't any changes to the consequence results for the different release categories. The changes to the L3PRA model included several enhancements including modeling the external hazards, crediting FLEX equipment, along with other changes. The 16 release categories that were initially used in phase 1 along with the three representative groups of release categories based on the doses at the EAB remained the same. The impact of these L3PRA model enhancements on the release category results was dependent of the sensitivity of the different accidents on these modeling changes. Accidents or release categories that were more sensitive to external event initiators had their associated frequencies increase which increased the risk associated with these categories. For the accidents and release categories that are mitigated by FLEX strategies they had their associated frequencies decrease which reduced the risk associated with these categories. There were several release categories that were not impacted by the L3PRA model enhancements, and their associated frequencies remained the same. As shown in figure 6, out of the sixteen release categories, eight had their frequencies increase, two had their frequencies decrease, and six of the release categories frequencies remained the same.

Figure 6: Release Category Impacts

In figure 7, the 16 release category results from the enhanced NRC's L3PRA model are shown on the LMP's F-C chart and provide more accurate risk-insights for the different release categories. This chart shows how the different groups expand when the L3PRA results that include external hazards and other modeling improvements are applied. This is a result of the sensitivity of the different release categories to the L3PRA model enhancements.

Where a licensee, or the NRC, might make a decision based on the magnitude of the consequence alone, the LMP methodology makes it easier to consider the frequency of the event, the magnitude of the associated consequences, and the associated uncertainties. The release categories that are closest to the F-C target would be the leading candidates to focus attention and resources.

Figure 7: Phase II results F-C Chart with Release Category Bins



4. CONCLUSION

The results from phase 1 and phase 2 of this project support the usefulness of the LMP methodology and associated tools for applications beyond the original intended applications for NLWR licensing. Specifically, the F-C curve coupled with Level 3 PRA results provides an enhanced understanding of reactor risks beyond the traditional risk metrics of CDF and LERF. These traditional risk metrics have been heavily used by the nuclear industry to better understand reactor risks and treat all core damage (CD) events the same. All CD events are not the same. Some of these events result in larger radioactive releases than others, follow different release pathways, and the timing of these events can vary drastically. Ultimately, Level 3 PRA results provide a more detailed understanding of the different accident risks that include this difference in CD events. This additional understanding of the severity and significance of the consequences coupled with the LMP's F-C curve can support integrated risk-informed decision-making by highlighting areas where safety margins exist. The LMP methodology was developed as a technology-inclusive process to apply to all reactor designs in the design and licensing phases. This research shows the utility of the LMP process when used on an operating reactor design and gives us a better understanding of the L3PRA results and how the consequence results relate to the corresponding frequencies.

This research did not implement the full range of the LMP methodology. The LMP's use of the F-C curve to support the selection of licensing basis events, safety classification of SSCs, and determination of DID adequacy is focused on new reactor design applications. Since this project evaluates technology representing operating reactors, the main focus of this research was to evaluate the F-C curve results to evaluate this technologies safety profile. There are several limitations to this research that can be evaluated in future work. Specifically, when aspects of the LMP guidance are not clear, the conservative interpretation of the Level 3 PRA model results were used. This includes using the TEDE for the non-evacuating cohort to represent the 30-day TEDE. It is not clear if evacuations should be credited, but if so, the results from this research would be over representing the consequences from the different release categories. Uncertainties associated with both the frequencies and consequences of the different release categories were not evaluated in this paper. Uncertainties are considered in the LMP approach and this is a limitation of these current results, but an area that is being considered.

For reactor designers, developers, and researchers it is worth understanding the LMP methodology before substantial efforts are put into developing a Level 3 PRA model. A deeper understanding of the methodology will help ensure the Level 3 PRA model is structured to provide the correct risk metrics. Instead of needing to modify the model, or the results, to fit the LMP method's requirements, it will be more effective and efficient to spend the time upfront to ensure the model is designed to produce the correct risk metrics. Some example areas that may be useful to consider when developing a Level 3 PRA model are:

- Correct Consequence Metric (TEDE), exposure duration, exposure pathways, treatment of protective actions,
- Ensure the model generates results at the EAB, and
- Ensure uncertainty can be propagated through both the consequence and frequency results.

This research, which started with the risk from internal events and internal flooding and has progressed to include risk results from external hazards, also highlights that the safety profile for an operating reactor is broadly consistent with the goals set in advanced non-LWR reactor licensing guidance and in-line with the NRC's safety goals. Both the phase 1 and phase 2 results of this FFR project show that using the LMP methodology for operating reactor technology is a feasible approach to leveraging level 3 PRA model results to provide enhanced risk-insights. These insights include the importance of considering both the consequence and the frequencies of the different release categories. A more deterministic approach used without the probabilistic component may not appropriately focus efforts on the most safety significant accidents. This type of research has potential to provide these additional insights. The F-C target lines, taken from NEI 18-04 and RG1.233, supports the NRC safety goals through the regulations that are used to anchor the target lines and can provide the overall "safety case" for a reactor design. In this case, the analyzed operating reactor design is shown to be consistent with the NRC's safety goals by using the LMP approach. There are opportunities for future research to gain more specific insights from this type of analysis.

Acknowledgements

The NRC staff's previous efforts in developing a L3PRA model and reviewing and endorsing the LMP methodology have made this research possible. This project would not have been possible without these substantial efforts.

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