USA – The Regulatory Background and Technical Perspectives on Multi-Unit Risk Considerations

Multi-Unit Risk Considerations for Operating Reactors and Advanced Light Water Reactors

In the United States, there are 32 sites with two operating light water reactors and three sites with three operating light water reactors in the U.S. When Vogtle Unit 3 and Unit 4 (two AP1000 units) become operational (planned for 2022) there will be one site with four reactor units. Another 22 sites operate with only one reactor unit. With few exceptions, in the U.S. probabilistic safety assessments (PSAs) of NPPs have focused on developing PSA models for single units. All PSA models, however, have modeled some key aspects of multi-unit impacts (e.g. site-wide initiators such as loss of offsite power and incorporated shared systems to the PSA models after an appropriate treatment of plant procedures). U.S. Nuclear Regulatory Commission (NRC) regulations, however, have always recognized the multi-unit accidents risk considerations in design, and policy considerations in a risk-informed performance manner.

Some examples of regulatory treatment of multi-unit risk considerations in design and siting are as follows: 10 CFR Part 50, Appendix A, General Design Criterion 5[1] states:

> *Structures, systems, and components important to safety shall not be shared among nuclear power units unless it can be shown that such sharing will not significantly impact their ability to perform their safety functions, including, in the event of an accident in one unit, an orderly shutdown and cooldown of the remaining units.*

10 CFR 100.11(b)[2], which provides requirements for determining the exclusion area, the low population zone, and the population center distance for multi-unit sites:

> *Subsection (b)(1): If the reactors are independent to the extent that an accident in one reactor would not initiate an accident in another, the size of the exclusion area, low population zone and population center distance shall be fulfilled with respect to each reactor individually.*
>
> *Subsection (b)(2): If the reactors are interconnected to the extent that an accident in one reactor could affect the safety of operation of any other, the size of the exclusion area, low population zone and population center distance shall be based on the assumption that all interconnected reactors emit their postulated fission product releases simultaneously.*

Some examples of U.S. NRC Commission views with respect to multi-unit risk considerations for the operating reactors are as follows:

In response to the accident at Three Mile Island, the NRC issued an action plan (NUREG-0660)[3]. Item II.B.8 involved a two-phase rulemaking proceeding on degraded-core accidents. In the second phase (termed the “long-term rulemaking”), the NRC identified the need to consider the effects of an accident in a reactor plant on an adjacent plant in a multiple reactor site. This issue was subsequently dropped at the Commission’s direction, as discussed in

the Staff Requirements Memorandum to SECY-82-1B[4]:

There are other issues listed in Item II.B.8 of NUREG-0660 that the Commission believes have minimal value for improved safety and, therefore, need not be considered further: namely, effects of severe accidents at multi-unit sites and post-accident recovery plans.

Moreover, the Commission's Safety Goals, which define acceptable risk, are applied on a per- reactor basis. NUREG-0880[5] summarizes comments made by the public as the Safety Goals were being formulated in the early 1980s:

Some commenters objected to the originally proposed individual and societal numerical guidelines because they were to be applied on a per-site basis. This would have resulted in tighter requirements being imposed on plants at multi-unit sites than at single-unit sites. The Commission decided not to impose a regulatory bias against multi-unit sites. Therefore, the quantitative design objectives were changed from risks per site to risk per plant.

Because of the Commission's decision to apply the Safety Goals on a per-reactor basis, as well as the advances in state-of-the art (e.g. lower than previously estimated source terms, slower progression of core damage accidents due accident mitigation strategies,) and plant safety enhancements due to post-Fukushima modifications, there has been no regulatory impetus to estimate the total risk of a multi-unit site for U.S. operating reactors..

Enhancement to Safety due to Post-Fukushima Orders

Operating experiences[6] as well as numerous other site-wide loss of offsite power events provide proof of multi-unit reactors accidents and the need to consider those risks in regulatory policy and decision making. The sequence of events during the Fukushima Daiichi accident has been reviewed extensively by the nuclear industry and the U.S. NRC[7,8]. That accident clearly demonstrated that multi-unit accidents are credible, and their risk can be an important contributor to the overall risk associated with the site.

Following the Fukushima Daiichi accident, the NRC established a Near-Term Task Force (NTTF) in response to a Commission direction. The NTTF developed a comprehensive set of recommendations and issued it to the Commission on August 12, 2011[7]. The subject report included several recommendations by a panel of NRC experts. Recommendation 2.3 stated that licensees should be ordered to perform seismic and flooding walk downs to identify plant-specific vulnerabilities against the current Design Basis. Recommendation 2.1 stated that licensees should be ordered to re-evaluate the seismic and flooding hazards at their sites against the NRC requirements and guidance imposed on new reactors. Consequently, the Commission issued directions outlining a set of near-term and long-term actions which should be implemented by the staff via a staff requirement memorandum (SRM) SECY-11-0124[9]. The NRC eventually submitted 50.54(f) letters requesting that licensees address recommendations 2.1 and 2.3 for seismic and flooding hazards[10]. NRC also issued an Order EA-12-0049[11]. This Order required a three-phase approach for mitigating beyond-design-basis external events. The

initial phase required the use of installed equipment and resources to maintain or restore core cooling, containment and spent fuel pool (SFP) cooling capabilities. The transition phase requires providing sufficient, portable, onsite equipment and consumables to maintain or restore these functions until they can be accomplished with resources brought from off site. The final phase requires obtaining sufficient offsite resources to sustain those functions indefinitely.

The order also stated these strategies must be capable of mitigating a simultaneous loss of all alternating current (ac) power and loss of normal access to the ultimate heat sink and have adequate capacity to address challenges to core cooling, containment, and SFP cooling capabilities at all units on a site.

In response to this order the U.S. nuclear power industry made various changes to their plants (e.g., procurement and sometimes installation of additional components, development of procedures) to address the Commission orders. Each plant installed new emergency response equipment, stored onsite and protected from natural hazards. NRC inspectors have verified that the strategies are in place at all the US nuclear power plants. Industry also established two national centers to store additional equipment.

Even though the Orders were issued to induvial reactor units, the modifications that were required to comply with the orders were focused on primarily on multi-unit accidents such as loss of all alternating currents and heat sink Consequently, the multi-unit risk component of all U.S. sites are lower compared to their levels prior to Fukushima event.

Margins Between Quantitative Safety Goals and Risk Metrics

The Nuclear Regulatory Commission (NRC) established its Safety Goal Policy in 1986[12]. In that policy, the NRC established two qualitative safety goals and supporting quantitative health objectives (QHOs). The qualitative safety goals were as follows: The operation of nuclear power plants would pose no significant additional risk to an individual, and the risks to society would be comparable to or less than those associated with other forms of generating electricity. The associated QHOs were as follows: (1) The risk to an average individual in the vicinity of a nuclear power plant of prompt fatalities that might result from reactor accidents should not exceed one-tenth of one percent (0.1 percent) of the sum of prompt fatality risks resulting from other accidents to which members of the U.S. population are generally exposed. (2) The risk to the population in the area near a nuclear power plant of cancer fatalities that might result from nuclear power plant operation should not exceed one-tenth of one percent (0.1 percent) of the sum of cancer fatality risks resulting from all other causes.

For regulatory decision making, NRC uses surrogate the subsidiary objectives, also referred to as “risk-metrics.” For plants licensed under 10 CFR 50 and 10 CFR 52 (e.g. AP1000), the risk-metrics for core damage frequency (CDF) is $1x10^{-4}$ /year. For plants licensed under 10 CFR 50, the risk-metric for large early release frequency (LERF) is $1x10^{-5}$ /year. For plants licensed under 10 CFR 52, the LERF metric is $1x10^{-6}$ per year. Appendix D of NUREG-1860[13], used risk analyses performed by NRC in the late 1980s and documented in NUREG-1150[14] to correlate the QHOs with risk-metrics.

In 2018, the Electric Power Research Institute (EPRI) performed a technical evaluation of margins between QHOs and the risk-metrics using various NRC studies that had demonstrated that (a) the amount of radioactivity releases during a core-damage event is substantially less than previously assumed, and (b) the rate of core-melt progression is slower than previous assumed (hence providing additional time to evacuate). Using these insights EPRI stated that there are significant margins (order of 10,000 between LERF and early fatality risk and order of 100 between CDF and latent fatality risk)[15].

NRC staff, when informed of the EPRI report (i.e., NRC has not performed a formal review of the report), informed EPRI and the industry that (a) QHOs are a subset of the Safety Goal Policy (a narrow focus on the numerical margins ignores the intention of the entirety of NRC's Safety Goal Policy), (b) the entirety of NRC responsibilities, rules, and policies should be considered when translating numerical margins to regulatory margins, and (c) staff should carefully consider the applicability of past studies for the purpose of estimating numerical margins when translating them to risk-informed decision making.

The NRC staff, however, did not refute the fact there is more margins than that was assumed when Appendix D of NUREG-1860 was prepared in 1980s since the follow-on work such as SOARCA studies have shown that core melt progression will be slower than estimated, and that sources-terms will be less than estimated[16].

Summary of the Planned Screening Approach that Staff will Use to Consider Multi-Unit Risk Consideration

In spite of the belief that multi-unit risks do not pose safety concerns, U.S. NRC is of the view that multi-unit risk considerations should be considered, qualitatively, or quantitatively in risk-informed decision making. Therefore, the NRC staff is in the process of using (a) analytical work relating to multi-unit risks, (b) insights gleaned from multi-unit PSAs and spent fuel pool risk assessments that have already been performed, and (3) the Level 3 PSA project that is underway at U.S. NRC, to develop a screening methodology to enable the U.S. NRC to glean risk insights at a site-specific level. Paragraphs below provide a synopsis reflective of the current status of that effort. An updated version will be provided by end of October 2019.

In 2012, a paper entitled "An Event Classification for Evaluating Site Risk in a Multi-Unit Nuclear Power Plant Probabilistic Risk Assessment" provides number of insights to develop an informed analysis to consider risk considerations for sites with two to three units[17]. That paper acknowledged that PSAs at multi-unit nuclear power consider risk from each unit separately and consider dependencies and interactions between the units informally and on an ad hoc basis. The paper highlighted that fact that the accident at the Fukushima nuclear power station underlined the importance and possibility of multi-unit accidents. The paper then provided six main factors (dependence classifications) that must be effectively accounted for, in assessing multi-unit considerations. These are:

- initiating events
- shared connections

- identical components
- proximity dependencies,
- human dependencies, and
- organizational dependencies.

In 2014, in response to some NRC staff questions about the magnitude to multi-unit risk, NRC undertook an initiative to develop a methodology to arrive at bounding estimates of multi-unit risks for reactors located on a given site. That bounding methodology is documented in a paper entitled “Scoping Estimate of Multi- Unit Accident Risk”[18].

From [18], when applied to three-unit site results in a scoping estimate of:

$$R_{(site,3)} \leq 3R_{(cci,1)} + 9R_{(sui,1)}$$

Here,

$R_{(site,3)}$ is the total risk from the three-unit site.

$R_{(cci,1)}$ is the risk from a single unit due to a common initiator such as an earthquake.

$R_{(sui,1)}$ is the risk from a single unit due to single unit initiators such as a loss-of-coolant accident.

It is important to note that as discussed before, the plant modifications implemented by US plants to meet additional requirements imposed on them because of Fukushima event prompted reductions in risk associated with common initiators {R(cci,1)}. For plants whose risk profile was dominated by loss of power events, these reductions in risk were substantial.

Based on the above, it is not unreasonable to expect that the risk at a site with three units is unlikely to be an order of magnitude larger than the risk associated with one unit. In fact, unless there are vulnerabilities that enable a release from one unit to cause difficulties for the operators of other units to safety shutdown the reactor, or relatively high common cause failure among across units, substantial increases in risk are not likely. Because of this, and in consideration of the margins that exist between the QHOs and U.S. NRC Safety Goals and the risk-metrics used to support risk-informed decision making, there is no impetus to require U.S. licensees with two or three reactor units to develop detailed multi-unit PSA models. The NRC will continue to evaluate multi-unit risk and plans to develop a method that adequately captures multi-unit risk consideration for use in risk-informed decision making.

Multi-Unit Risk Consideration for non-LWR or Advanced Reactors with More than One Module

More recently, the NRC issued Revision 3 to Chapter 19 of NUREG-0800[19] to include considerations for multi-module risk. This update states:

1. *For small, modular integral pressurized water reactor designs, the staff reviews the results and description of the applicant’s risk assessment for a single reactor module; and, if the applicant is seeking approval of an application for a plant containing multiple modules, the staff reviews the applicant’s assessment of risk from accidents that could*

affect multiple modules to ensure appropriate treatment of important insights related to multi-module design and operation. The staff will verify that the applicant has:

i. *Used a systematic process to identify accident sequences, including significant human errors, that lead to multiple module core damages or large releases and described them in the application*

ii. *Selected alternative features, operational strategies, and design options to prevent these sequences from occurring and demonstrated that these accident sequences are not significant contributors to risk. These operational strategies should also provide reasonable assurance that there is sufficient ability to mitigate multiple core damages accidents.*

To support the future licensing of non-LWR plants, U.S. industry is developing a technology-inclusive, risk-informed, and performance-based guidance for the selection of licensing basis events, the classification of systems, structures and components, and the evaluation of defense-in-depth[20]. This guidance states:

If applicable, the PRA should include event sequences involving two or more reactor modules as well as two or more sources of radioactive material. This enables the identification and evaluation of risk management strategies for reactor modules and sources within the scope of a single application to ensure that sequences involving multiple reactor modules and sources are not risk-significant.

In addition, the American Society and Mechanical Engineers and the American Nuclear Society have developed a trial-use standard for the performance of PSAs for advanced non-LWR nuclear power plants[21]. Section 1.2 of this standard states:

This standard establishes requirements for a PRA for advanced non-LWR NPPs. The requirements in this standard were developed for a broad range of PRA scopes that may include the following:

(a) Different sources of radioactive material both within and outside the reactor core but within the boundaries of the plant whose risks are to be determined in the PRA scope selected by the user. The technical requirements in this trial-use version of the standard are limited to sources of radioactive material within the reactor coolant system (RCS) pressure boundary (RCPB). Technical requirements for other sources of radioactive material such as the spent fuel system are deferred to future editions of this standard;

(d) Different event sequence end states, including core or plant damage states (PDSs), and release categories that are sufficient to characterize mechanistic source terms, including releases from event sequences involving two or more reactor units or modules for PRAs on multireactor or multiunit plants;

Research Activities

In the research arena, the NRC Office of Nuclear Regulatory Research (RES) is in the intermediate stages of an effort to create an integrated Level 3 PSA that includes the effects of multiple units, as well as the risk from all radiation sources onsite, such as the spent fuel pool. The ongoing integrated site Level 3 PSA study is being performed for research purposes. Although some potential future uses within the USNRC's regulatory framework have been identified, this Level 3 PSA is not intended to support a specific risk-informed application. Instead, the fundamental objectives of this study are to[22,23]:

1) Develop a contemporary Level 3 PSA generally based on current state-of-practice methods, models, data, and analytical tools that:
    - Reflects technical advances since the last USNRC-sponsored Level 3 PSAs were performed as part of the NUREG-1150 study.
    - Addresses risk contributors not previously considered, including concurrent accidents involving multiple co-located radiological sources (i.e., multi-unit accidents).
2) Extract new risk insights to:
    - Enhance regulatory decision making.
    - Help focus limited resources on issues most directly related to USNRC's mission to protect public health and safety.
3) Enhance USNRC staff's internal PSA capability and expertise.
4) Improve PSA documentation to make information more accessible, retrievable, and understandable.
5) Obtain insight into the technical feasibility and cost of developing new Level 3 PSAs.

Although this Level 3 PSA study is generally being performed consistent with current standards and state-of-practice using existing PSA technology, there are some technical elements that necessitate methodological development due to a lack of sufficient experience to define a current state-of-practice. One such technical element is the Integrated Site PSA (i.e., multi-unit or multi-source PSA) technical element.

References

1. Title 10 Code of Federal Regulations Part 50, Appendix A, General Design Criterion 5, *Sharing of Structures, Systems, and Components*. Available at: https://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-appa.html
2. Title 10 Code of Federal Regulations Part 100, Subsection 11, *Determination of Exclusion Area, Low Population Zone, and Population Center Distance*. Available at: https://www.nrc.gov/reading-rm/doc-collections/cfr/part100/part100-0011.html
3. U.S. Nuclear Regulatory Commission, *NRC Action Plan Developed as a Result of the TMI-2 Accident*, NUREG-0660, 1980. Available at: https://www.nrc.gov/docs/ML0724/ML072470526.pdf.
4. U.S. Nuclear Regulatory Commission, *Regulatory Background on Multiunit Risk,* 2013. Available at: https://www.nrc.gov/docs/ML1325/ML13255A370.pdf.

5. U.S. Nuclear Regulatory Commission, *Safety Goals for Nuclear Power Plant Operation*, NUREG-0880, Rev. 1, 1983. Available at: https://www.nrc.gov/docs/ML0717/ML071770230.pdf.
6. E. Vial, V. Rebour, and B. Perrin, *Severe storm resulting in partial plant flooding in 'Le Blayais' nuclear power plant*, 2005.
7. U.S. Nuclear Regulatory Commission, *Recommendations for Enhancing Reactor Safety in the 21st Century, the Near-Term Task Force Review of Insights from the Fukushima Dai-ichi Accident*, 2011. Available at: https://www.nrc.gov/docs/ML1118/ML111861807.pdf.
8. Institute of Nuclear Power Operations, *Lessons Learned from the Nuclear Accident at the Fukushima Daiichi Nuclear Power Station, Rev. 0*, *INPO 11-005 Addendum*, 2012.
9. U.S. Nuclear Regulatory Commission, *Staff Requirements – SECY-11-0124 – Recommended Actions to be Taken Without Delay from the Near-Term Task Force Report*, 2011. Available at: https://www.nrc.gov/docs/ML1129/ML112911571.pdf
10. U.S. Nuclear Regulatory Commission, *Request for Information Pursuant to Title 10 of the Code of Federal Regulations 50.54(f) Regarding Recommendations 2.1, 2.3, and 9.3 of the Near-Term Task Force Review of Insights from the Fukushima Dai-ichi Accident*, 2012. Available at: https://www.nrc.gov/docs/ML1205/ML12053A340.pdf
11. U.S. Nuclear Regulatory Commission, *Issuance of Order to Modify Licenses with Regard to Requirements for Mitigation Strategies for Beyond-Design-Basis External Events*, 2012. Available at: https://www.nrc.gov/docs/ML1205/ML12054A735.pdf
12. U.S. Nuclear Regulatory Commission, *Safety Goals for the Operations of Nuclear Power Plants; Policy Statement*, Federal Register, Vol. 51, pp. 30028 (51 FR 30028), 1986.
13. U.S. Nuclear Regulatory Commission, *Feasibility Study for a Risk-Informed and Performance-Based Regulatory Structure for Future Plant Licensing (NUREG-1860)*, 2007.
14. U.S. Nuclear Regulatory Commission, *Severe Accident Risks: An Assessment of Five U.S. Nuclear Power Plants (NUREG-1150)*, 1990.
15. Electric Power Research Institute, *Insights on Risk Margins at Nuclear Power Plants*, 2018.
16. US. Nuclear Regulatory Commission, *State-of-the-Art Reactor Consequence Analyses Project Volume 1: Peach Bottom Integrated Analysis (NUREG/CR-7110)*, 2013. Available at: https://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr7110/v1/
17. S. Schroer and M. Modarres, *An Event Classification Schema for Evaluating Site Risk in a Multi-Unit Nuclear Power Plant Probabilistic Risk Assessment*, 2013. Available at: https://www.sciencedirect.com/science/article/pii/S0951832013000756
18. M. Stutzke, *Scoping Estimates of Multiunit Accident Risk*, 2014. Available at: http://meetingsandconferences.com/psam12/proceedings/paper/paper_96_1.pdf
19. U.S. Nuclear Regulatory Commission, *Chapter 19.0 Probabilistic Risk Assessment and Severe Accident Evaluation for New Reactors, Revision 3, NUREG-0800*, 2015. Available at: https://www.nrc.gov/docs/ML1508/ML15089A068.pdf.
20. Nuclear Energy Institute, *Modernization of Technical Requirements for Licensing of Advanced Non-Light Water Reactors: Risk-Informed Performance-Based Guidance for Non-Light Water Reactor Licensing Basis Development*, NEI 18-04, Draft N, ADAMS Accession No. ML18242A469, September 28, 2018.

21. The American Society of Mechanical Engineers and the American Nuclear Society, *Probabilistic Risk Assessment Standard for Advanced Non-LWR Nuclear Power Plants*, ASME/ANS RA-S-1.4-2013, Trial Use and Pilot Application, December 9, 2013.
22. U.S. Nuclear Regulatory Commission. *Update on Staff Plans to Apply the Full-Scope Site Level 3 PRA Project Results to the NRC's Regulatory Framework. SECY-12-0123.* Washington, DC: U.S. Nuclear Regulatory Commission; 2012. Available at: http://www.nrc.gov/reading-rm/doc-collections/commission/secys/2012/2012-0123scy.pdf.
23. U.S. Nuclear Regulatory Commission. *Technical Analysis Approach Plan for Level 3 PRA Project. Rev. 0B - Working Draft.* U.S. Nuclear Regulatory Commission; 2013. Available at: https://www.nrc.gov/docs/ML1329/ML13296A064.pdf.