NRC-RES' Sitewide, All Hazards Level 3 PRA Project: Integrated Site Risk for Two-Unit Site

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Abstract: The U.S. Nuclear Regulatory Commission (NRC) has performed a full-scope, sitewide Level 3 probabilistic risk assessment (PRA) project (L3PRA project) for a two-unit, pressurized-water reactor reference plant. The scope of this project includes all hazards (internal and external) and all radiological sources on the reference site: 1) two, nearly identical reactors; 2) two, hydraulically connected spent fuel pools (SFPs), and 3) a dry cask storage (DCS) facility. The NRC has published a series of reports documenting the results of all of these PRA efforts.

In addition to the single unit PRAs performed for NRC's L3PRA project, a previously, never-performed task was added: integrated site risk (ISR). ISR is defined as the aggregation of risks from all relevant radiological sources. Of particular interest are those accident scenarios for which both reactors and the SFPs experience simultaneous radiological releases starting from at-power conditions.

To support the ISR task, a sitewide dependency assessment was performed first. The results of this assessment identified that: 1) the two reactors were independent except for unavoidable dependencies (e.g., identical components, sharing of electric power) and 2) there were potential dependencies between the reactors and the SFPs with respect to shared resources (e.g., water supplies, operators). Consequently, the focus of the ISR task was limited to the most challenging accident scenarios that involved the two reactors and the SFPs simultaneously (i.e., a multi-source scenario).

Due to limited time and resources, the ISR task focused on demonstrating a proof-of-concept, rather than full multi-source quantification. Using the results of the sitewide dependency assessment with the multi-unit (MU) results from the Level 1 and Level 2 PRAs, a relatively large seismic event was identified as a good candidate scenario to analyze, since such an event can lead to a severe accident for both the reactors and SFPs. A scenario description was developed, including the timing of reactor and SFP behavior, the timing of plant conditions, and the timing of required operator actions. MU release category definitions were combined with SFP release categories to define release categories for the combination of the reactors and the SFPs. Then, multi-unit consequence results were calculated with the MACCS multi-source capability and combined with release category frequencies to generate multi-source risk.

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1. INTRODUCTION

The United States (U.S.) Nuclear Regulatory Commission (NRC) is performing a full-scope site Level 3 probabilistic risk assessment (PRA) project (L3PRA project) for a two-unit pressurized-water reactor reference plant. The scope of this all-hazards, sitewide L3PRA project includes estimation of multi-unit (MU) risk and multi-source risk, as part of an evaluation of integrated site risk (ISR). This effort was directed by the Commission (see Staff Requirements Memorandum [1] that resulted from SECY-11-0089 [2]) and includes the following radiological sources on the reference site:

- two (nearly identical) operating pressurized water reactor units (Unit 1 and Unit 2)
- two, hydraulically connected spent fuel pools (SFPs) for each reactor unit (Unit 1 and Unit 2)
- an independent dry cask storage (DCS) facility

Previous NRC PRA efforts, such as NUREG-1150 [3], did not include consideration of risk from the SFPs or DCS, or risk of MU accidents. Consequently, ISR is a new task that has not been previously addressed in NRC PRA efforts. Note, for the L3PRA project, the U.S. nuclear power industry's proposed Diverse and Flexible Coping Strategies (FLEX) were addressed only in a sensitivity study, since the project's modeling freeze date is 2012.

In general, PRA has traditionally been performed for single units only, though the Seabrook PRA [4] was an early industry PRA effort that considered two-unit risk.[1] In response to the 2011 Great Japan Earthquake and the events at the Fukushima Daiichi nuclear power station,[2] there has been increased interest in MU risk in both the U.S. and internationally. Zhou and Modarres [10] summarize the history and current status of multi-unit PRA (MUPRA) development. In addition, there have been multiple responses to these events from the NRC, including lessons learned [11] and implications for PRA [12].

At present, draft public reports for all of the L3PRA project PRAs - single unit reactor Level 1, 2, and 3 PRAs, SFPs, DCS, and ISR - have been published. A previous paper [13] previewed some of the ISR task results to provide preliminary MU insights that might be applicable to advanced reactors.

2. INTEGRATED SITE RISK APPROACH

Due to limited time and resources, the ISR task focused on demonstrating a proof-of-concept, rather than full ISR quantification. Consequently, the goal of the ISR approach for the NRC's L3PRA project is to identify and describe a single scenario in which both reactors and the SFPs would have simultaneous (e.g., within 24 hours of reactor trip) radiological releases.

The approach for the ISR task relies heavily on previously performed L3PRA project work, such as the single unit Level 1 and 2 PRAs, the SFP Level 1 and 2 PRAs, and multi-unit core damage frequency (MUCDF) results. At a high-level, the ISR approach consists of the following steps:

1. Perform a sitewide dependency assessment
2. Develop MUCDF results
3. Develop MU Level 2 and Level 3 PRA results
4. Define an illustrative multi-source risk scenario
5. Develop multi-source Level 3 PRA results for the illustrative scenario

Step 1 is briefly summarized in this paper below. The remainder of the paper focuses on Steps 4 and 5. Companion papers describe the NRC's MU Level 1 PRA results and the approach used to develop MU Level 2 PRA results.

In addition to the limited experience in performing MUPRAs described above, there is also limited guidance for developing Level 1 MUPRAs. Two reports by the International Atomic Energy Agency (IAEA) [14, 15] and an Electric Power Research Institute (EPRI) report [16] were used extensively in the L3PRA project's ISR task, especially for performing Steps 1 and 2. Also, there is little experience in integrating reactor risk with SFP risk. Two such efforts [17, 18] that integrate a single unit Level 2 PRA model with an SFP PRA were used by the L3PRA project.

3. SITEWIDE DEPENDENCY ASSESSMENT

The overall ISR task included a sitewide dependency assessment that is based upon the previous work by the IAEA [14, 15] and EPRI [16]. In particular, the L3PRA project's sitewide dependency assessment approach used a phased approach similar to that in the EPRI report and dependency categories that overlap those defined in both the IAEA and EPRI reports. The sitewide dependency assessment was performed from the perspective of both Level 1 and Level 2 PRAs.

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[1] Note that the second unit at the Seabrook site was never built.
[2] See, for example, two reports released by the Government of Japan [5, 6], an IAEA report [7], and two Institute of Nuclear Power Operations INPO) reports [8, 9].

For the L3PRA project, the three phases of sitewide dependency assessment were defined as follows:
- Phase 1 Assessment: Sitewide and multi-unit initiating events
- Phase 2 Assessment: Shared physical resources, and shared or connected systems, structures, and components (SSCs)
- Phase 3 Assessment: Identical components, proximity dependencies, human or organizational dependencies, accident propagation between units, and potential hazards correlations

The sitewide dependency assessment was performed first for the two reactors. Then, potential dependencies between the SFPs and the reactors were assessed.[3]

The results of this assessment identified that:
1. Only seismic events were important potential sitewide initiating events for both the reactors and the SFPs.
2. There were potential dependencies between the reactors in post-core damage conditions (i.e., SU Level 2 PRA) and the SFPs experience post-fuel damage conditions with respect to shared resources (e.g., portable pumps, water supplies) and human and organizational factors (i.e., sharing of available operators).
3. There were no other Phase 2 (e.g., shared physical resources or SSCs) or Phase 3 (e.g., identical components) dependencies.

Because of the general lack of dependencies between the reactors and the SFPs, a formal logic model did not need to be developed in order to evaluate multi-source risk.

4. DEFINITION OF THE MULTI-SOURCE SCENARIO

When considering the objective of estimating "sitewide risk," the L3PRA project team decided to focus on potential "worst case" scenarios that involved sitewide dependencies and consequences that occur close in time. This section describes how this "worst case" scenario was developed and defined.

4.1. Approach for Defining the Illustrative Multi-Source Scenario

Because the sitewide dependency assessment (discussed in Section 3) identified a few sitewide dependencies between the reactors and SFPs, the ISR task focused on the identification and definition of an illustrative multi-source scenario that involved both the reactors and the SFPs. As mentioned in Section 2, a single illustrative multi-source scenario was defined for a "proof of concept" analysis. Given that only one multi-source scenario was going to be defined, the L3PRA project team decided to focus on a potential "worst case" scenario that involved sitewide dependencies and consequences that occur close in time. For example:
- What consequences could occur at the "same time" (e.g., nearly simultaneous releases from both reactors and SFPs)?
- How could such a scenario occur (e.g., what dependencies and accident conditions must exist)?

The approach used to select and define an illustrative multi-source scenario involved all members of the project team. The project team used a variety of information sources, including:
- the sitewide dependency assessment discussed in Section 3
- the identification of MU and sitewide IEs
- the MU Level 1 risk results reported in Section 6 of the L3PRA project's ISR report [19]
- the details (e.g., time available for operator actions) of the single source SFP Level 1 and 2 PRA

[3] There were no potential dependencies identified between the reactors and the DCS facility.

4.2. Selection of Seismic Bin 6 for the Illustrative Multi-Source Scenario

The illustrative multi-source scenario that was selected by the project team was a large seismic event (i.e., seismic bin 6) for at-power conditions. The project team considered several factors in selecting seismic bin 6 for the illustrative scenario. Examples of these factors and their impact on the ISR scenario definition are:

- From the Phase 1 sitewide dependency assessment, the multi-source scenario should be a seismic event.
- From the at-power,[4] MU Level 1 PRA assessment:
  - The combined MUCDF result for seismic events is over 50 percent of total MUCDF.
  - Of the seismic events, bins 3 through 6 are the largest contributors to total MUCDF.
- From the single source, SFP Level 1 and 2 PRA results for significant fuel uncovery frequency (SFUF):
  - Seismic bins 5 through 7 are the most important for SFPs during the operating cycle phases (OCPs) with both reactors at power.
  - Mitigation is not credited for seismic bins 7 and 8 because: (1) the extreme sloshing in these cases will make the refuel floor immediately uninhabitable due to high radiation levels associated with low SFP water level (i.e., fuel uncovery is immediate), (2) the fuel handling building (FHB) itself may experience significant damage and thus be difficult to access, and (3) the potential for these extreme events to further degrade human performance.
  - A simplified MELCOR model was used to make several calculations such as available times for operator actions for the SFP Level 1 and 2 PRAs (including the amount of time available to align makeup, depending on the size of the leak), the amount of sloshing (affected by the seismic bin), and the OCP (which affects decay heat).

4.3. Description of Illustrative Multi-Source Scenario

The scenario that was selected and developed for the ISR task is summarized in Table 1. Table 1 consists of a timeline of major events, especially those that are important to modeling inputs used in the Level 1, Level 2, and Level 3 PRAs for both the reactors and the SFPs.

The accident progression for the reactors and the SFPs shown in Table 1 is set up by the initial conditions (i.e., both reactors at power and SFPs in nominal conditions), the specific seismic event (i.e., seismic bin 6), and response to the seismic event. For simplicity, both reactors are assumed to experience core damage, containment failure, and releases at the same time. Because only at-power conditions were addressed, only two operating cycle phases needed to be considered for the SFPs (i.e., AAN1 and AAN5[5]).

Also, only three release categories (RCs)[6] for the reactors were selected for the illustrative scenario:

- containment isolation failure (CIF)
- late containment failure (LCF)
- intermediate containment failure due to burn (ICF-BURN)

[4] Note, since a seismic event was selected for the illustrative scenario, only at-power conditions could be considered because the L3PRA project low-power and shutdown (LPSD) PRA only addresses internal events, due to limitations in (1) state-of-practice methods for addressing other hazard categories during LPSD conditions and (2) overall project resources.

[5] AAN1 and AAN5 involve both reactors at power and the SFPs in nominal conditions (i.e., no fuel handling activities). They differ only in the time since one of the reactors was shut down for refueling.

[6] MU Level 2 PRA is computationally challenging especially due to the potential number of RC combinations for two or more reactors. Consequently, a few of the more risk-important RCs were selected for the illustrative ISR scenario.

Table 1: Timing of Key Events in the Illustrative Multi-Source Scenario

Time	Event(s)	Plant/SFP Conditions	Notes/Assumptions
-0	Initial conditions	Both reactors at power	
		Both SFPs in "nominal" state[7]	
0	**Large seismic event**	Seismic bin 6	
	Loss of offsite power and SBO	Sitewide event	These losses are relevant to both reactors and the SFPs.
	Significant water sloshing and liner failures	Both SFPs	These failures are assumed to be simultaneous.
	Extensive structural damage from seismic event	Sitewide	Buildings relevant to both reactors and SFPs are affected.
	Extensive equipment failure from seismic event	Sitewide	Equipment relevant to both reactors and SFPs are affected.
3 hours	**General Emergency is declared**		
See "event column"	**Core damage at:** - CIF = 16 hours[8] - LCF = 3.9 hours - ICF-BURN = 16 hours[2]	Reactors	Reactors are assumed to experience core damage at the same time for the same RCs.
12 ½ hours	**Evacuation complete, including:** - 45 minutes for notifications - Additional 8 ¾ hours to evacuate emergency planning zone	SFPs and reactors	The same evacuation model is used for all seismic bins.
~10 hours	**Time available for external makeup for SFPs**	SFPs	This is an EDMG strategy that uses a portable pump, fire water storage tanks, etc.
~22 hours	**Time available for containment spray cooling[9]**	Reactors	This is an EDMG strategy that uses a portable pump, fire water storage tanks, etc.
See "event column"	**Containment failure**: - CIF = 0 hours - LCF = 48 hours - ICF-BURN = 28 hours	Reactors (containment failure assumed to occur at the same time for Units 1 & 2)	Containment failures are assumed to be simultaneous for the same RCs.
See "event column"	**Containment releases**: - CIF = 21 & 18 hours - LCF = 55 & 158 hours - ICF-BURN = 28 & 33 hours	Reactors Xenon and Iodine releases, respectively, for each RC (both units at the same time)	Containment releases are assumed to be simultaneous for the same RCs.
See "event column"	**SFP releases:** - 60 hours (AAN1) - 153 hours (AAN5)	SFPs	

[7] No fuel handling activities.
[8] Core damage occurs later for CIF and ICF-BURN because, for these RCs, AFW is assumed to operate for 4 hours before batteries are depleted.
[9] LCF and ICF-BURN only

The selection of seismic bin 6 for the illustrative multi-source scenario prescribed many of the needed event details for quantifying the joint risk of both reactors and the SFPs. The most important of those details is occurrence of a large seismic event that:

- contributes significantly to MU and SFP risk
- causes widespread site SSC damage, leading to:
    - limited effectiveness of reactor Level 1 PRA mitigation strategies
    - large SFP inventory losses that require mitigation
    - loss of offsite power (LOOP) and station blackout (SBO) conditions which limit the effective mitigation strategies for the SFPs, but do allow for the possibility of mitigation strategies being effective

As noted above, the project team focused on the sharing of physical resources and the associated sharing of human resources between the reactors and SFPs, as well as the associated timing of potential mitigation strategies. Both of these sitewide dependencies involve the use of Extensive Damage Mitigation Guideline (EDMG) strategies that are modeled in the single unit, reactor Level 2 PRA. These reactor EDMG strategies require the same equipment, water resources, and operators that are modeled for the SFP makeup mitigation strategy. In addition, required timing for both the reactor and SFP mitigation strategies is similar (e.g., within the traditional 24-hour mission time) only for seismic bin 6. For larger seismic events, SFP mitigation strategies are not feasible (i.e., no mitigation is possible for seismic bins 7 and 8). For less damaging seismic events (i.e., seismic bins 1 through 5), SFP mitigation strategies are not needed until many days following the beginning of the accident scenario. The need for and timing of the SFP mitigation strategies is based on some unique modeling in the SFP Level 1 and 2 PRA, in which both liner failures and water sloshing out of the SFPs are projected to occur.

5. MULTI-SOURCE SCENARIO RESULTS

The approach and consequence results for the illustrative multi-source scenario are summarized below.

5.1. Approach for Developing Results for Illustrative Multi-Source Scenario Involving Two Reactors and SFPs

Since the illustrative multi-source scenario that the project team defined involved essentially simultaneous releases from both reactors and both SFPs, the MU Level 2 PRA results and SFP Level 2 PRA results were combined. In turn, these combined RCFs were used as inputs to NRC's MACCS code, using its multi-source capability [20] to develop multi-source consequences.

It is well-known within the community of Level 2 PRA that there are computational challenges associated with the large number of potential MU RCs. Consequently, a limited number of the most consequential MU RCs were addressed in the MU Level 2 PRA task (e.g., CIF-CIF and CIF-LCF). Table 2 shows the selected combinations of MU and SFP RCs[10] and their combined RCFs.

For this analysis, explicit MACCS multi-source analyses involving SFP source terms were not available at the time of writing. Instead, drawing on the insights from MU consequence analyses, it was assumed that the multi-source RCs could be reasonably approximated by the summation of the reactor MU consequences and the SFP consequences from the SFP Level 3 PRA. Because all RC combinations were assumed to be initiated by a severe seismic event, the MU consequences (assuming a degraded evacuation) were used. Table 3 shows some of the results[11] that were generated.

[10] SFP RCs include a Level 1 PRA to Level 2 PRA transition bin representing (e.g. SFU5), similar to a plant damage state in a reactor PRA, and an operating cycle phase (e.g., AAN1), that comes from discretization of the reactor and SFP operating cycle.

[11] Results for total economic costs are not shown in Table 3, whereas results presented later include this risk measure.

Table 2: Frequency-Weighted Multi-Source Consequences

RC Combination	Combined RCF (/reactor-critical year)
CIF–CIF–SFU5-AAN1	6.65E-10
CIF–CIF–SFU5-AAN5	1.97E-09
LCF–ICF-BURN–SFU5-AAN1	1.29E-09
LCF–ICF-BURN–SFU5-AAN5	3.82E-09
CIF–CIF–SFU6-AAN1	1.99E-09
CIF–CIF–SFU6-AAN5	5.90E-09
LCF–ICF-BURN–SFU6-AAN1	3.88E-09
LCF–ICF-BURN–SFU6-AAN5	1.15E-08

Table 3: Reactor At-Power MU and SFP Consequences for Selected Multi-Source RC Combinations

RC combination	Individual Latent Fatality Risk, 0–10 miles (cases/person)			Collective Total Effective Dose, 0–50 miles (person-rem)		
	MU	SFP	MU +SFP	MU	SFP	MU +SFP
CIF, CIF, SFU5-AAN1	9.54E-04	1.20E-03	2.15E-03	6.56E+05	1.70E+06	2.36E+06
CIF, CIF, SFU5-AAN5	9.54E-04	7.60E-04	1.71E-03	6.56E+05	4.20E+05	1.08E+06
LCF, ICF-BURN, SFU5-AAN1	8.98E-04	1.20E-03	2.10E-03	5.43E+05	1.70E+06	2.24E+06
LCF, ICF-BURN, SFU5-AAN5	8.98E-04	7.60E-04	1.66E-03	5.43E+05	4.20E+05	9.63E+05
CIF, CIF, SFU6-AAN1	9.54E-04	1.20E-03	2.15E-03	6.56E+05	1.70E+06	2.36E+06
CIF, CIF, SFU6-AAN5	9.54E-04	7.60E-04	1.71E-03	6.56E+05	4.20E+05	1.08E+06
LCF, ICF-BURN, SFU6-AAN1	8.98E-04	1.20E-03	2.10E-03	5.43E+05	1.70E+06	2.24E+06
LCF, ICF-BURN, SFU6-AAN5	8.98E-04	7.60E-04	1.66E-03	5.43E+05	4.20E+05	9.63E+05

5.2. Summary of Results for Illustrative Multi-Source Scenario

Context for the magnitude of MU risk compared to single unit risk is provided in Table 4. This table shows the risk from all modeled RC combinations for MU weather-related losses of offsite power (LOOPWR), MU seismic bin 6 (EQK-BIN-6), and multi-source risk (simultaneous accidents for both reactors and the SFPs) for seismic bin 6, and compares these results to the single unit risk estimates from the reactor at-power, reactor low power and shutdown (LPSD), and SFP analyses. Caution should be used in this comparison, because the MU results do not include the full set of initiators analyzed in the single unit analyses. However, it may be noted that total MU LOOPWR and EQK-BIN-6 risks are substantially less than those for the reactor at-power or LPSD but are comparable to those for the SFPs. The multi-source (i.e., combined reactor-SFP) risk is substantially less than that for either the reactor at-power, reactor LPSD, or SFPs. The L3PRA project's ISR report [19] provides further details on the multi-source scenario development and results.

Table 4: Summary of Risk Measures – SU, MU, and Multi-Source

Scope Piece	Release Freq. (/yr)	Individual Latent Fatality Risk, 0–10 miles (/yr)[1]	Collective Total Effective Dose Risk (person-rem/yr), 0–50 miles[1]	Total Economic Cost Risk, 0–50 miles (2015$/yr)[1]
At-Power (Internal events and internal floods) for a single unit	6.9E-05	2.5E-08	9.9	80,000
At-Power (All hazards[2]) for a single unit	1.6E-04	6.4E-08	27	230,000
LPSD (Internal events) for a single unit	4.7E-05	1.4E-08	9.7	150,000
SFP (all hazards)	5.8E-07	6.3E-10	0.52	8,400
All MU LOOPWR[3]	5.52E-07	3.35E-10	0.14	1,220
All MU EQK-BIN-6[4]	2.47E-06	1.84E-09	0.94	9,630
Multi-source (i.e., (i.e., simultaneous accidents for both reactors and SFP) for EQK-BIN-6	3.10E-08	5.55E-11	0.041	589

Note 1: Results are a frequency-weighted sum of all RCs. Reactor at-power results are based on reactor-critical-years. To convert the risk metric of the **reactor at-power** from per reactor-critical-year to per calendar-year, multiply the result by the plant availability factor of 0.93. Note, the resulting reactor, at-power, calendar-year risk does not include the risk associated with reactor shutdown operations during the calendar year.

Note 2: Includes at-power internal events, internal floods, internal fires, seismic events, and high wind events. Also, note that these values (and the other values reported in this table) do not include credit for the U.S. nuclear power industry's proposed Diverse and Flexible Coping Strategies (FLEX), as well as other more recent plant changes, such as the installation of new reactor coolant pump shutdown seals. When these other changes are credited, the total release frequency from a single unit is reduced to 1.0E-04/rcy.

Note 3: LOOPWR – weather-related LOOP; the results shown are for simultaneous core damage at both units due to dependencies such as shared, connected, or identical structures, systems, and components [SSCs]).

Note 4: EQK-BIN-6 – seismic hazard bin 6; the results shown are for simultaneous core damage at both units due to their co-location on the same site during a seismic bin 6 earthquake.

6. CONCLUSIONS

The NRC's L3PRA project developed proof-of-concept, multi-source risk results, for an illustrative scenario. Combined MU and SFP consequences were developed for an illustrative large seismic event for which some potential dependencies between the reactors and SFPs were identified. Eight combinations of MURCs and SFP operating cycle phases were addressed and results for three risk measures were provided in this paper:

- individual latent fatality risk
- collective total effective dose risk
- total economic cost risk

The multi-source (i.e., combined MU and SFP) consequence results cannot be directly compared with the single source results because the scope of the analyses is different (e.g., total SFP results include both at-power and shutdown conditions). It can be generally concluded, however, that the results for the combined reactor and SFP risk (i.e., multi-source risk) are substantially less than that for either the reactor at-power, reactor LPSD, or SFPs.

Integrated site risk was not calculated for two reasons: 1) multi-source risk results provide new insights while integrated site risk would not, and 2) scope limitations prevented calculation of all of the inputs needed to make a calculation of ISR (e.g., risk associated with accident scenarios involving only one reactor and both SPFs).

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