SCOPING ESTIMATES OF MULTIUNIT NUCLEAR POWER PLANT SITE RISKS

Introduction and Background

This appendix develops and applies a scoping approach for estimating the total site risk due to accidents that may affect one or more NPPs at a common site. A complete assessment of multiunit risk requires the development of a site Level 3 PRA that delineates multiunit accidents that may occur during all site operating configurations and all hazards. The NRC staff is developing this type of PRA for one multiunit site, but results are not anticipated until 2015. In contrast, the approach taken in this appendix uses information from a single-unit Level 3 PRA to develop a scoping estimate of the total site risk.

Development of the Scoping Approach

Multiunit accident sequences may be caused by two classes of initiating events:

- Common-Cause Initiators (CCIs): Initiators that simultaneously challenge all of the units at the site. CCIs include initiators that are caused by external hazards (e.g., earthquakes, severe weather).

- Single-Unit Initiators (SUIs): Initiators that occur at one unit. SUIs generally include initiators caused by internal hazards such as internal events (e.g., loss of main feedwater, loss of coolant accidents), internal floods, and internal fires. SUIs may cause multiunit accidents due to cross-unit dependencies such as shared support systems, spatial interactions (e.g., internal flood and internal fire propagation pathways), common-cause failures, or operator actions.

Since SUIs only occur at one unit, multiunit accident sequences caused by SUIs must consider how accident sequences are initiated in the subsequent units (i.e., the units that did not experience the SUI). In order to distinguish among the types of multiunit accident sequences caused by SUIs, the following taxonomy has been used:

- Cascading sequence: A multi-source accident sequence caused by an SUI that causes core damage and release from the unit where the SUI occurred and also in one or more additional units.

- Propagating sequence: A multi-source accident sequence caused by an SUI that does not cause core damage in the unit where the SUI occurred, but causes core damage and release in one or more additional units.

- Restricted sequence: A single-source accident sequence caused by an SUI that only causes core damage and release in the unit where the SUI occurred (i.e., no other unit is affected).

The following sections show how these definitions may be used to develop a scoping estimate of site risk by summing the contributions from CCIs and SUIs.

Review of Combinatorial Analysis

In order to understand the development of the total site risk scoping estimate, it is useful to review certain aspects of combinatorial analysis. Consider a three-unit site with units labeled Unit 1, Unit 2, and Unit 3. There are seven possible outcomes that involve release from one or more units, as listed below:

- Single-unit outcomes: Unit 1, Unit 2, Unit 3
- Dual-unit outcomes: Unit 1 and Unit 2, Unit 1 and Unit 3, Unit 2 and Unit 3
- Triple-unit outcomes: Units 1 and Unit 2 and Unit 3

Specifically, there are three single-unit outcomes, three dual-unit outcomes, and one triple-unit outcome. The various outcomes can be depicted on a Venn diagram, as shown in Figure 1, where all of the outcomes that affect a specific unit are included within a circle.

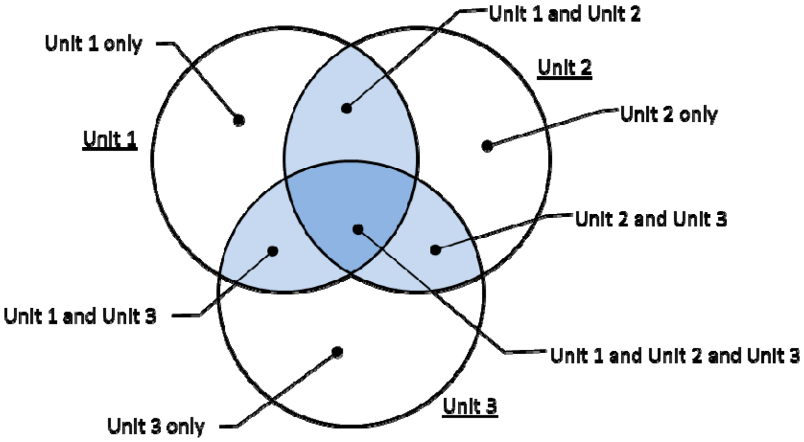

Figure 1. Venn Diagram Depicting Multiunit Accidents.

In general, for a site that has n units:

$$\text{number of outcomes that involve exactly } k \text{ out of } n \text{ units} = \binom{n}{k} \quad (1)$$

It is sometimes necessary to determine the number of outcomes that include a specific unit. In the three-unit example above, there is one single-unit outcome that includes Unit 2, two dual-unit outcomes that include Unit 2, and one triple-unit outcome that includes Unit 2. In general, for a site that has n units:

$$\begin{array}{l}\text{number of outcomes that include a specific unit}\\ \text{and involve exactly } k \text{ out of } n \text{ units}\end{array} = \binom{n-1}{k-1} \qquad (2)$$

Equations (1) and (2) can be combined and reduced to yield the following identity:

$$\begin{array}{l}\text{number of outcomes that exclude a specific unit}\\ \text{and involve exactly } k \text{ out of } n \text{ units}\end{array} = \binom{n}{k} - \binom{n-1}{k-1} = \binom{n-1}{k} \qquad (3)$$

Contribution from Common-Cause Initiators

Consider the occurrence of a CCI at a three-unit site with units labeled Unit 1, Unit 2, and Unit 3, and define the following events:

$$\begin{array}{l} U1 = \text{release from Unit 1}\\ U2 = \text{release from Unit 2}\\ U3 = \text{release from Unit 3}\end{array} \qquad (4)$$

From these fundamental definitions, define the following compound events:

$$\begin{array}{l} U1 \cap \overline{U2} \cap \overline{U3} = \text{release from only Unit 1}\\ \overline{U1} \cap U2 \cap \overline{U3} = \text{release from only Unit 2}\\ \overline{U1} \cap \overline{U2} \cap U3 = \text{release from only Unit 3}\\ U1 \cap U2 \cap \overline{U3} = \text{release from only Unit 1 and Unit 2}\\ U1 \cap \overline{U2} \cap U3 = \text{release from only Unit 1 and Unit 3}\\ \overline{U1} \cap U2 \cap U3 = \text{release from only Unit 2 and Unit 3}\\ U1 \cap U2 \cap U3 = \text{release from Unit1, Unit 2 and Unit 3}\end{array} \qquad (5)$$

The compound events defined in Equation (5) are depicted in Figure 1, the Venn diagram. Equation (5) states that there are exactly seven possible outcomes that result in release, given the occurrence of a CCI at a three-unit site.

Assume that the units at a site are identical. It then follows that the probability that a CCI causes core damage and release from a specific combination of units at the site only depends on the number of units in the combination. Returning to the three-unit site example, the assumption implies that:

$$\begin{aligned}\Pr\{U1 \cap \overline{U2} \cap \overline{U3} \mid CCI\} &= \Pr\{\overline{U1} \cap U2 \cap \overline{U3} \mid CCI\} = \Pr\{\overline{U1} \cap \overline{U2} \cap U3 \mid CCI\} \\ \Pr\{U1 \cap U2 \cap \overline{U3} \mid CCI\} &= \Pr\{U1 \cap \overline{U2} \cap U3 \mid CCI\} = \Pr\{\overline{U1} \cap U2 \cap U3 \mid CCI\}\end{aligned} \tag{6}$$

The assumption can be applied to a site that has an arbitrary number of units through the following definitions:

$$\begin{aligned}&n = \text{number of identical units at the site} \\ &f_{CCI} = \text{frequency of CCIs} \\ &p_{k,CCI}^{(n)} = \Pr\{\text{release from exactly } k \text{ of } n \text{ units} \mid \text{CCI}\} \\ &C_{k,CCI}^{(n)} = \text{consequence due to release from exactly } k \text{ of } n \text{ units after CCI}\end{aligned} \tag{7}$$

Using the definitions provided in Equations (1) and (7), the contribution to site risk from CCIs is given by:

$$R_{S,CCI}^{(n)} = f_{CCI} \sum_{k=1}^{n} \binom{n}{k} p_{k,CCI}^{(n)}\, C_{k,CCI}^{(n)} \tag{8}$$

Assume that the consequence of a multiunit accident is proportional to the number of units that experience core damage and release[1]:

$$C_{k,CCI}^{(n)} = k\, C_{1,CCI}^{(n)} \tag{9}$$

Substituting Equation (9) into Equation (8) and simplifying yields:

$$R_{S,CCI}^{(n)} = n\, f_{CCI}\, C_{1,CCI}^{(n)} \sum_{k=1}^{n} \binom{n-1}{k-1} p_{k,CCI}^{(n)} \tag{10}$$

Considering the explanation of Equation (2), the summation on the right-hand side of Equation (10) is the probability that a specific unit experiences core damage and release given the occurrence of an CCI. That is, the summation accounts for all possible combinations of multiunit accidents that include a specific unit. As a result, the per-unit risk due to CCIs (as determined by a typical single-unit PRA) is:

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[1] The NRC staff has made informal scoping calculations of multi-unit accident consequences, based on doubling the source terms used in the SOARCA project. The results indicate that, with respect to health-related consequences, multi-unit risk is subadditive. Therefore, use of the assumption expressed in Equation (9) results in a conservative estimate of the site risk.

$$R_{\text{single-unit},CCI} = f_{CCI} C_{1,CCI}^{(n)} \sum_{k=1}^{n} \binom{n-1}{k-1} p_{k,CCI}^{(n)} \tag{11}$$

As a result:

$$R_{S,CCI}^{(n)} = n R_{\text{single-unit},CCI} \tag{12}$$

Therefore, assuming that (1) the site has identical units, and that (2) the consequences of a multiunit accident are proportional to the number of units that experience core damage and release, the site risk due to CCIs is the product of the number of units at the site and the per-unit risk due to CCIs as estimated by a typical single-unit PRA.

Contribution from Single-Unit Initiators

In order to estimate the contribution to site risk from SUIs, it is important to recognize that an SUI may occur in any unit, and that the occurrence of an SUI may result in cascading, propagating, or restricted sequences. Consider the occurrence of an SUI at Unit1, $SUI1$, which is located at a three-unit site. Figure 2 illustrates the possible restricted (black arrow), cascading (blue arrows), and propagating sequences (red arrows) that result in core damage and release that are caused by the occurrence of $SUI1$.

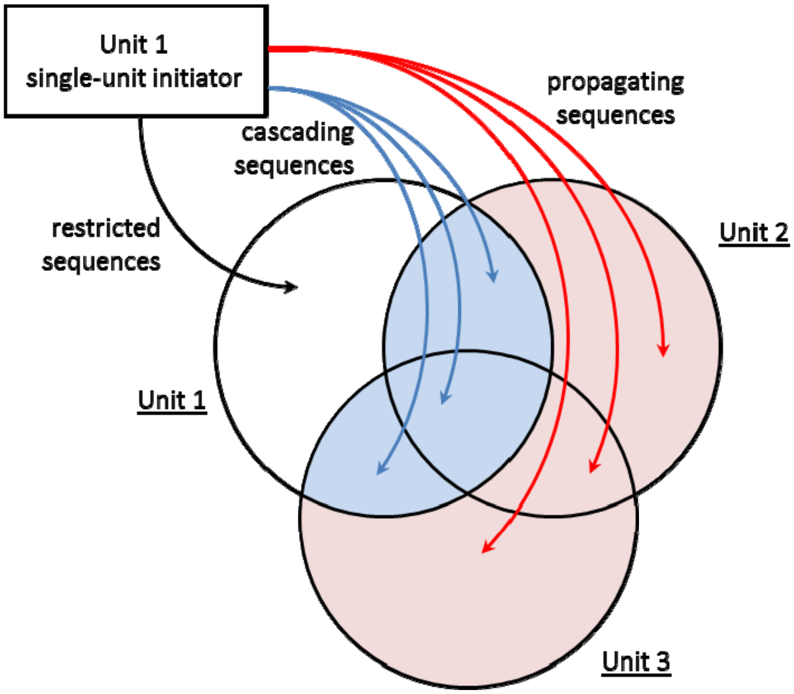


Figure 2. Restricted, Cascading, and Propagating Sequences Caused by a Single-Unit Initiator.

The contribution to site risk from this Unit-1 SUI is:

$$R^{(3)}_{1,SUI} = \begin{aligned}[t] & f_{SUI,1}\Pr\{U1 \cap \overline{U2} \cap \overline{U3} \mid SUI1\}\, C\{Unit\ 1\ release\} && \textit{restricted} \\ & + f_{SUI,1}\Pr\{U1 \cap U2 \cap \overline{U3} \mid SUI1\}\, C\{Units\ 1\ and\ 2\ release\} && \textit{cascading} \\ & + f_{SUI,1}\Pr\{U1 \cap \overline{U2} \cap U3 \mid SUI1\}\, C\{Units\ 1\ and\ 3\ release\} && \textit{cascading} \\ & + f_{SUI,1}\Pr\{U1 \cap U2 \cap U3 \mid SUI1\}\, C\{Units\ 1,2\ and\ 3\ release\} && \textit{cascading} \\ & + f_{SUI,1}\Pr\{\overline{U1} \cap U2 \cap \overline{U3} \mid SUI1\}\, C\{Unit\ 2\ release\} && \textit{propagating} \\ & + f_{SUI,1}\Pr\{\overline{U1} \cap \overline{U2} \cap U3 \mid SUI1\}\, C\{Unit\ 3\ release\} && \textit{propagating} \\ & + f_{SUI,1}\Pr\{\overline{U1} \cap U2 \cap U3 \mid SUI1\}\, C\{Units\ 2\ and\ 3\ release\} && \textit{propagating} \end{aligned} \tag{13}$$

There are similar expressions for the contributions to site risk from SUIs that occur at Unit 2 and Unit 3, and the total site risk due to SUIs is the sum of these three expressions. These expressions can be generalized by assuming that the units at a site are identical, and by defining the following quantities:

$$\begin{aligned} f_{SUI} &= \text{frequency of SUIs at a specific unit} \\ p^{(n)}_{k,SUI} &= \text{Pr\{release from exactly } k \text{ of } n \text{ units due to restricted and} \\ &\quad \text{cascading sequences | SUI\}} \\ q^{(n)}_{k,SUI} &= \text{Pr\{release from exactly } k \text{ of } n \text{ units due to propagating sequences | SUI\}} \\ C^{(n)}_{k,SUI} &= \text{consequence due to release from exactly } k \text{ of } n \text{ units after SUI} \end{aligned} \tag{14}$$

In terms of the three-unit example, the restricted contribution probabilities are:

$$\begin{aligned} p^{(3)}_{1,SUI} &= \Pr\{U1 \cap \overline{U2} \cap \overline{U3} \mid SUI1\} \\ &= \Pr\{\overline{U1} \cap U2 \cap \overline{U3} \mid SUI2\} \\ &= \Pr\{\overline{U1} \cap \overline{U2} \cap U3 \mid SUI3\} \end{aligned} \tag{15}$$

The cascading contribution probabilities are:

$$\begin{aligned}
p_{2,SUI}^{(3)} &= \Pr\{U1 \cap U2 \cap \overline{U3} \mid SUI1\} \\
&= \Pr\{U1 \cap \overline{U2} \cap U3 \mid SUI1\} \\
&= \Pr\{U1 \cap U2 \cap \overline{U3} \mid SUI2\} \\
&= \Pr\{\overline{U1} \cap U2 \cap U3 \mid SUI2\} \\
&= \Pr\{U1 \cap \overline{U2} \cap U3 \mid SUI3\} \\
&= \Pr\{\overline{U1} \cap U2 \cap U3 \mid SUI3\} \\
p_{3,SUI}^{(3)} &= \Pr\{U1 \cap U2 \cap U3 \mid SUI1\} \\
&= \Pr\{U1 \cap U2 \cap U3 \mid SUI2\} \\
&= \Pr\{U1 \cap U2 \cap U3 \mid SUI3\}
\end{aligned} \tag{16}$$

The propagating contribution probabilities are:

$$\begin{aligned}
q_{1,SUI}^{(3)} &= \Pr\{\overline{U1} \cap U2 \cap \overline{U3} \mid SUI1\} \\
&= \Pr\{\overline{U1} \cap \overline{U2} \cap U3 \mid SUI1\} \\
&= \Pr\{U1 \cap \overline{U2} \cap \overline{U3} \mid SUI2\} \\
&= \Pr\{\overline{U1} \cap \overline{U2} \cap U3 \mid SUI2\} \\
&= \Pr\{U1 \cap \overline{U2} \cap \overline{U3} \mid SUI3\} \\
&= \Pr\{\overline{U1} \cap U2 \cap \overline{U3} \mid SUI3\} \\
q_{2,SUI}^{(3)} &= \Pr\{\overline{U1} \cap U2 \cap U3 \mid SUI1\} \\
&= \Pr\{U1 \cap \overline{U2} \cap U3 \mid SUI2\} \\
&= \Pr\{U1 \cap U2 \cap \overline{U3} \mid SUI3\}
\end{aligned} \tag{17}$$

Using the definitions provided in Equations (2), (3) and (14), the contribution to site risk from SUIs is given by:

$$R_{S,SUI}^{(n)} = n\, f_{SUI} \sum_{k=1}^{n} \binom{n-1}{k-1} p_{k,SUI}^{(n)}\, C_{k,SUI}^{(n)} + n f_{SUI} \sum_{k=1}^{n-1} \binom{n-1}{k} q_{k,SUI}^{(n)} C_{k,SUI}^{(n)} \tag{18}$$

Assume that the consequence of a multiunit accident is proportional to the number of units that experience core damage and release:

$$C_{k,SUI}^{(n)} = k\, C_{1,SUI}^{(n)} \tag{19}$$

Substituting Equation (19) into Equation (18):

$$R_{S,SUI}^{(n)} = n\, f_{SUI}\, C_{1,SUI}^{(n)} \sum_{k=1}^{n} k \binom{n-1}{k-1} p_{k,SUI}^{(n)} + n f_{SUI} C_{1,SUI}^{(n)} \sum_{k=1}^{n-1} k \binom{n-1}{k} q_{k,SUI}^{(n)} \tag{20}$$

Equation (20) can be further simplified by noting that $k = 1 + (k-1)$, which yields:

$$\begin{aligned} R_{S,SUI}^{(n)} &= n\, f_{SUI}\, C_{1,SUI}^{(n)} \left[\sum_{k=1}^{n} \binom{n-1}{k-1} p_{k,SUI}^{(n)} + \sum_{k=1}^{n} (k-1) \binom{n-1}{k-1} p_{k,SUI}^{(n)} + \sum_{k=1}^{n-1} k \binom{n-1}{k} q_{k,SUI}^{(n)} \right] \\ &= n\, f_{SUI}\, C_{1,SUI}^{(n)} \left[\sum_{k=1}^{n} \binom{n-1}{k-1} p_{k,SUI}^{(n)} + (n-1) \sum_{k=2}^{n} \binom{n-2}{k-2} (p_{k,SUI}^{(n)} + q_{k-1,SUI}^{(n)}) \right] \end{aligned} \tag{21}$$

Similar to Equation (11), the first summation is the per-unit risk due to SUIs (as determined by a typical single-unit PRA):

$$R_{\text{single-unit},SUI} = f_{SUI} C_{1,SUI}^{(n)} \sum_{k=1}^{n} \binom{n-1}{k-1} p_{k,SUI}^{(n)} \tag{22}$$

As a result:

$$R_{S,SUI}^{(n)} = n R_{\text{single-unit},SUI} + n(n-1) f_{SUI}\, C_{1,SUI}^{(n)} \sum_{k=2}^{n} \binom{n-2}{k-2} (p_{k,SUI}^{(n)} + q_{k-1,SUI}^{(n)}) \tag{23}$$

Further reduction of Equation (23) can be achieved by noting that:

$$p_{k,SUI}^{(n)} + q_{k-1,SUI}^{(n)} = (p_{k,SUI}^{(n)} + p_{k-1,SUI}^{(n)}) - (p_{k-1,SUI}^{(n)} - q_{k-1,SUI}^{(n)}) \tag{24}$$

So:

$$\begin{aligned} R_{S,SUI}^{(n)} &= n R_{\text{single-unit},SUI} + n(n-1) f_{SUI}\, C_{1,SUI}^{(n)} \sum_{k=2}^{n} \binom{n-2}{k-2} (p_{k,SUI}^{(n)} + p_{k-1,SUI}^{(n)}) \\ &\quad - n(n-1) f_{SUI}\, C_{1,SUI}^{(n)} \sum_{k=2}^{n} \binom{n-2}{k-2} (p_{k-1,SUI}^{(n)} - q_{k-1,SUI}^{(n)}) \end{aligned} \tag{25}$$

Expanding out the first summation shows that:

$$\begin{aligned}
\sum_{k=2}^{n}\binom{n-2}{k-2}(p_{k,SUI}^{(n)}+p_{k-1,SUI}^{(n)}) &= \binom{n-2}{0}(p_{2,SUI}^{(n)}+p_{1,SUI}^{(n)})+\binom{n-2}{1}(p_{3,SUI}^{(n)}+p_{2,SUI}^{(n)}) \\
&\quad +\cdots+\binom{n-2}{n-2}(p_{n,SUI}^{(n)}+p_{n-1,SUI}^{(n)}) \\
&= p_{1,SUI}^{(n)}+\left[\binom{n-2}{0}+\binom{n-2}{1}\right]p_{2,SUI}^{(n)}+\cdots \\
&\quad +\left[\binom{n-2}{k-2}+\binom{n-2}{k-1}\right]p_{k,SUI}^{(n)}+\cdots+p_{n,SUI}^{(n)} \\
&= \sum_{k=1}^{n}\binom{n-1}{k-1}p_{k,SUI}^{(n)}
\end{aligned} \tag{26}$$

Combining Equations (22), (25) and (26):

$$R_{S,SUI}^{(n)} = n^2\, R_{\text{single-unit},SUI} - n\,(n-1) f_{SUI}\, C_{1,SUI}^{(n)} \sum_{k=2}^{n}\binom{n-2}{k-2}(p_{k-1,SUI}^{(n)} - q_{k-1,SUI}^{(n)}) \tag{27}$$

Scoping Estimates of Site Risk

The total site can be found by summing the contribution from CCIs, as given by Equation (12), and the contribution from SUIs, as given by Equation (27):

$$\begin{aligned}
R_S^{(n)} &= R_{S,CCI}^{(n)} + R_{S,SUI}^{(n)} \\
&= n\, R_{\text{single-unit},CCI} + n^2\, R_{\text{single-unit},SUI} - n\,(n-1) f_{SUI}\, C_{1,SUI}^{(n)} \sum_{k=2}^{n}\binom{n-2}{k-2}(p_{k-1,SUI}^{(n)} - q_{k-1,SUI}^{(n)})
\end{aligned} \tag{28}$$

A multiunit PRA is required to estimate the restricted, cascading, and propagating contribution probabilities (the p*'s* and q*'s*) in Equation (28). However, a useful bound on the total site risk is:

$$R_S^{(n)} < n\, R_{\text{single-unit},CCI} + n^2\, R_{\text{single-unit},SUI} \tag{29}$$

This bound follows from the observation that:

$$p_{k,SUI}^{(n)} \geq q_{k,SUI}^{(n)} \tag{30}$$

In order for an SUI to propagate into other units, there must be a sequence of events in the initiating unit (i.e., the unit where the SUI occurred) that cause an initiating event in one or more of the other units. As a result, the propagating probabilities (the q*'s*) are the product of the conditional probability that the subsequent unit(s) experience an initiating event given an SUI and the conditional probability that the subsequent unit(s) experiences core damage and release. In contrast, the cascading probabilities (the *p's*) do not include the conditional probability that that subsequent unit(s) experience an initiating event because it is assumed that subsequent units are shutdown once core damage occurs in the initiating unit. That is, for cascading sequences, the conditional probability that subsequent unit(s) experiences an initiating event is identically 1.0.

Note that the bound on total site risk given in Equation (29) can be estimated from the results of a typical single-unit Level 3 PRA.

Application of the Scoping Approach

The Commission's Safety Goals are expressed in terms of quantitative health objectives (QHOs) for individual early fatality risk (IEFR) and individual latent cancer fatality risk (ILCFR) on a per-unit basis. There are no Safety Goals or QHOs that apply to total site risk. However, it is reasonable to conclude that the risks of multiunit sites are acceptable if they are less than the established per-unit QHOs. Moreover, the recently completed State-of-the-Art Reactor Consequence Analysis (SOARCA), NUREG-1935, showed that IEFR is vanishingly small for the plants and accident scenarios included in the analysis. As result, application of the scoping approach has focused on estimating the site ILCFR.

Neither the staff nor licensees have developed single-unit Level 3 PRA models that report ILCFR. The staff maintains a set of Standardized Plant Analysis of Risk (SPAR) models, which provide estimates of core-damage frequencies (CDFs) due to internal initiating events for all operating plants. In addition, the SPAR models have been expanded to include estimates of CDFs due to selected external events for a limited number of operating reactors. Although several proof-of-concept Level 2 SPAR models (which address containment performance by estimating accident release frequencies) have been developed, these Level 2 models are not routinely used for regulatory decision making. Many licensees have developed limited-scope Level 3 PRA models to support the assessment of severe accident mitigation alternatives (SAMAs) in conjunction with license renewals. However, estimation of ILCFR is not required to support the value-impact analyses of SAMAs. As result, the scoping approach was applied by developing CDF estimates for SUIs and CCIs, and utilizing a frequency-weighted average conditional probability of latent cancer fatality (CPLCF) given core damage has occurred.

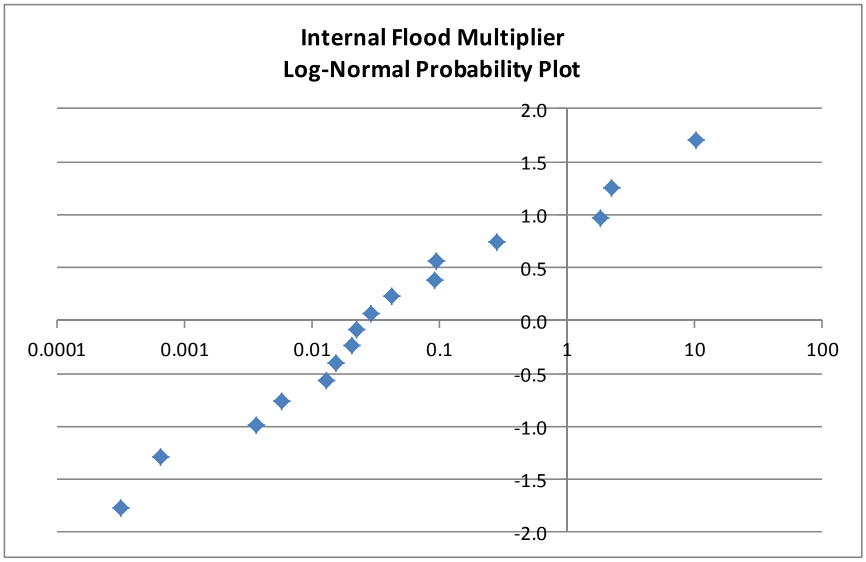
It was assumed that the CDFs of SUIs could be estimated by summing the CDFs due to internal initiating events, internal flooding events, and internal fire events. For all multiunit sites, internal initiating event CDFs were obtained from the SAPHIRE 8 SPAR Models, Version 8.15, dated September 23, 2010. CDFs due to internal floods and internal fires were obtained from the SPAR-EE Models Review, dated February 2011, for those plants that have external event SPAR models. Internal flood and internal fire multipliers (ratios) were developed for those plants that do not have external event SPAR models. These multipliers were determined by developing a set of multipliers (the ratio of the internal flood CDF to the internal initiating event

CDF, and the ratio of the internal fire CDF to the internal initiating event CDF), fitting a log-normal probability distribution to the set of multipliers, and estimating the 80th percentile. Table 1 provides the analysis details for the internal flood multiplier, which is based on the SPAR-EE information. Table 2 provides the analysis details for the internal fire multiplier, which is based on the SPAR-EE information supplemented with information obtained from license amendment requests pertaining to 10 CFR 50.48(c) – adoption of National Fire Protection Association Standard NFPA 805.

Table 1. Development of Internal Flood Multiplier.

Index	Site	Internal Events	Internal Floods	Flood Multiplier	ln(Multiplier)	Kimball Ranks	z-deviate
1	Fermi	1.65E-05	5.31E-09	0.00032	-8.042	0.038	-1.772
2	Davis Besse	4.61E-06	2.99E-09	0.0006	-7.341	0.099	-1.285
3	Turkey Point	2.70E-06	1.00E-08	0.0037	-5.598	0.161	-0.992
4	Summer	1.41E-05	8.24E-08	0.0058	-5.142	0.222	-0.766
5	Limerick 2	2.55E-06	3.32E-08	0.013	-4.341	0.283	-0.574
6	Limerick 1	2.62E-06	4.10E-08	0.016	-4.157	0.344	-0.401
7	Peach Bottom 2	2.57E-06	5.33E-08	0.021	-3.876	0.405	-0.240
8	Peach Bottom 3	1.39E-06	3.12E-08	0.022	-3.797	0.466	-0.084
9	Callaway	2.43E-05	7.08E-07	0.029	-3.536	0.528	0.069
10	Kewaunee	1.11E-05	4.76E-07	0.043	-3.149	0.589	0.224
11	Duane Arnold	5.47E-06	5.01E-07	0.092	-2.390	0.650	0.385
12	Wolf Creek	1.07E-05	1.03E-06	0.096	-2.341	0.711	0.556
13	Indian Point 3	1.06E-05	3.05E-06	0.288	-1.246	0.772	0.746
14	Salem	4.44E-05	8.29E-05	1.867	0.624	0.833	0.967
15	Monticello	2.63E-06	5.89E-06	2.240	0.806	0.894	1.251
16	Surry	4.85E-06	5.04E-05	10.392	2.341	0.956	1.702

minimum	3.2E-04	slope	0.329
maximum	10.392	intercept	1.038
average	0.946	mu	-3.158
median	0.026	sigma	3.042
		80th percentile	0.550



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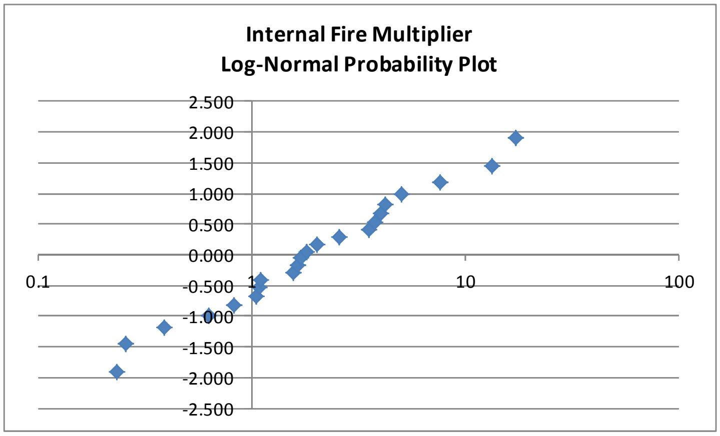
[2] The values in this table are considered representative of each plant because they were generated from an NRC SPAR model for that plant. The tabulated values may not reflect the licensee's own PRA analysis based on their most current models.

Table 2. Development of Internal Fire Multiplier.

Index	Site	Internal Events	Internal Fires	Source	Fire Multiplier	ln(Multiplier)	Kimball Ranks	z-deviate
1	Turkey Point	2.70E-06	6.30E-07	NFPA 805	0.23	-1.455	0.028	-1.910
2	Peach Bottom 2	2.57E-06	6.60E-07	SPAR-EE	0.26	-1.359	0.073	-1.454
3	D.C. Cook	3.34E-05	1.30E-05	NFPA 805	0.39	-0.944	0.118	-1.185
4	Salem	4.44E-05	2.80E-05	SPAR-EE	0.63	-0.461	0.163	-0.983
5	Callaway	2.43E-05	2.02E-05	SPAR-EE	0.83	-0.185	0.208	-0.814
6	Limerick 2	2.55E-06	2.69E-06	SPAR-EE	1.05	0.053	0.253	-0.666
7	Monticello	2.63E-06	2.87E-06	SPAR-EE	1.09	0.087	0.298	-0.531
8	Surry	4.85E-06	5.33E-06	SPAR-EE	1.10	0.094	0.343	-0.405
9	Limerick 1	2.62E-06	4.15E-06	SPAR-EE	1.58	0.460	0.388	-0.285
10	Summer	1.41E-05	2.34E-05	SPAR-EE	1.66	0.507	0.433	-0.170
11	Burnswick	8.73E-06	1.50E-05	NFPA 805	1.72	0.541	0.478	-0.056
12	Nine Mile Point	1.15E-05	2.10E-05	NFPA 805	1.83	0.602	0.522	0.056
13	Davis Besse	4.61E-06	9.34E-06	SPAR-EE	2.03	0.706	0.567	0.170
14	Farley	2.30E-05	5.90E-05	NFPA 805	2.57	0.942	0.612	0.285
15	Duane Arnold	5.47E-06	1.95E-05	SPAR-EE	3.56	1.271	0.657	0.405
16	Fermi	1.65E-05	6.22E-05	SPAR-EE	3.77	1.327	0.702	0.531
17	Peach Bottom 3	1.39E-06	5.62E-06	SPAR-EE	4.04	1.397	0.747	0.666
18	Oconee	1.44E-05	6.10E-05	NFPA 805	4.24	1.444	0.792	0.814
19	Indian Point 3	1.06E-05	5.40E-05	SPAR-EE	5.09	1.628	0.837	0.983
20	Kewaunee	1.11E-05	8.46E-05	SPAR-EE	7.62	2.031	0.882	1.185
21	Wolf Creek	1.07E-05	1.44E-04	SPAR-EE	13.46	2.600	0.927	1.454
22	Prairie Island	3.00E-06	5.20E-05	NFPA 805	17.33	2.853	0.972	1.910
				min	0.257		slope	0.836
				max	17.333		intercept	-0.537
				average	3.612		mu	1.197
				median	1.826		sigma	0.643
							80th percentile	5.683



[3]

It was assumed that the CDFs of CCIs could be estimated by summing the CDFs due to seismic events and tornados. For multiunit sites located in the Central and Eastern United States, seismic CDFs were obtained from the Safety/Risk Assessment developed for GI-199,

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[3] The values in this table are considered representative of each plant because they were generated from an NRC SPAR model for that plant, supplemented with information from licensee amendment requests associated with NFPA 805. The tabulated values may not reflect the licensee's own PRA analysis based on their most current models.

"Implications of Updated Probabilistic Seismic Hazard Estimates in Central and Eastern United States on Existing Plants," which was completed in September 2010. The seismic CDF for Diablo Canyon was obtained from the licensee's SAMA analysis. The seismic CDF for Palo Verde was estimated by the staff shortly after the March 11, 2010 accident at the Fukushima Dai-ichi facility occurred, using the methods of GI-199. CDFs due to tornados were estimated from information contained in NUREG/CR-4461, "Tornado Climatology of the Contiguous United States," assuming that CDF occurs when the wind speed exceeds 130 mph. The 130 mph criteria is suggested by NEI 12-06, "Diverse and Flexible Coping Strategies (FLEX) Implementation Guide," Revision 0, August 2012, and provides a conservative bound on the actual tornado CDF. Other types of external events (e.g., external floods, hurricanes, etc.) also contribute to the CDFs of CCIs; however, no CDF estimates for these types of external events have been made by the staff or by licensees.

The consequences of a core-damage accident vary, depending on the nature of the accident (the type of initiating event and the specific sequence) and the location of the plant (demographics and meteorology). A survey of the available accident consequence analyses, including SOARCA and NUREG-1150, suggests that the CPLCF ranges from about 10^{-5} to 10^{-3} for all types of accidents. Based on this survey, it was conservatively assumed that the CPLCF was 10^{-3}, regardless of the nature of the accident (SUI or CCI) and the site location.

Table 3 compiles the available information and provides estimates of the total site ILCFR for each operating multi-site site. In general, Equation (29) was applied to develop these estimates, with two special exceptions. The single-unit FitzPatrick site is located near the two units at the Nine Mile Point site, and the single-unit Hope Creek site is located near the two units at the Salem site. The ILCFR estimates for these special cases were summed to produce an estimate for the combined FitzPatrick/Nine Mile Point site and an estimate for the combined Hope Creek/Salem site.

Table 3. Scoping Estimates of Multi-Unit Site Risks.

	Single-Unit Initiators								Common-Ca	
	Int. Events	Internal Flood			Internal Fire			Total	Seismic	
Units	CDF	Source	Multiplier	CDF	Source	Multiplier	CDF	CDF	Source	CDF
2	7.2E-06		0.55	4.0E-06		5.7	4.1E-05	5.2E-05	GI-199	4.1E-06
2	5.6E-05		0.55	3.1E-05		5.7	3.2E-04	4.1E-04	GI-199	4.8E-05
2	8.7E-06		0.55	4.8E-06		5.7	4.9E-05	6.3E-05	GI-199	7.3E-06
3	4.1E-06		0.55	2.2E-06		5.7	2.3E-05	2.9E-05	GI-199	5.4E-06
2	8.7E-06		0.55	4.8E-06	NFPA 805		1.5E-05	2.9E-05	GI-199	1.5E-05
2	1.3E-05		0.55	6.9E-06		5.7	7.1E-05	9.1E-05	GI-199	5.8E-06
2	2.1E-05		0.55	1.1E-05		5.7	1.2E-04	1.5E-04	GI-199	1.2E-05
2	3.0E-05		0.55	1.6E-05		5.7	1.7E-04	2.1E-04	GI-199	3.7E-05
2	1.5E-05		0.55	8.4E-06		5.7	8.7E-05	1.1E-04	GI-199	4.0E-06
2	3.3E-05		0.55	1.8E-05	NFPA 805		1.3E-05	6.5E-05	GI-199	1.2E-05
2	1.6E-05		0.55	8.7E-06		5.7	9.1E-05	1.2E-04	licensee	4.0E-05
2	8.5E-07		0.55	4.7E-07		5.7	4.8E-06	6.2E-06	GI-199	1.9E-05
2	2.3E-05		0.55	1.3E-05	NFPA 805		5.9E-05	9.5E-05	GI-199	2.8E-05
1	4.3E-06		0.55	2.3E-06		5.7	2.4E-05	3.1E-05	GI-199	6.1E-06
2	1.2E-05		0.55	6.3E-06	NFPA 805		2.1E-05	3.9E-05	GI-199	5.6E-06
2	7.2E-06		0.55	4.0E-06		5.7	4.1E-05	5.2E-05	GI-199	2.2E-06
1	5.3E-06		0.55	2.9E-06		5.7	3.0E-05	3.9E-05	GI-199	2.8E-06
2	3.4E-05	SPAR-EE		8.3E-05	SPAR-EE		2.8E-05	1.5E-04	GI-199	7.4E-06
2	9.7E-06	SPAR-EE		3.1E-06	SPAR-EE		5.4E-05	6.7E-05	GI-199	1.0E-04
2	3.2E-06		0.55	1.8E-06		5.7	1.8E-05	2.3E-05	GI-199	3.7E-06
2	2.3E-06	SPAR-EE		4.1E-08	SPAR-EE		4.2E-06	6.4E-06	GI-199	5.3E-05
2	7.4E-06		0.55	4.0E-06		5.7	4.2E-05	5.3E-05	GI-199	3.1E-05
2	4.1E-06		0.55	2.2E-06		5.7	2.3E-05	3.0E-05	GI-199	1.5E-05
2	1.3E-05		0.55	7.0E-06		5.7	7.3E-05	9.3E-05	GI-199	4.4E-05
3	1.4E-05		0.55	7.9E-06	NFPA 805		6.1E-05	8.3E-05	GI-199	4.3E-05
3	8.9E-06		0.55	4.9E-06		5.7	5.1E-05	6.4E-05	see note	3.8E-05
2	3.4E-06	SPAR-EE		5.3E-08	SPAR-EE		6.6E-07	4.1E-06	GI-199	2.4E-05
2	9.3E-06		0.55	5.1E-06		5.7	5.3E-05	6.8E-05	GI-199	1.1E-05
2	4.1E-06		0.55	2.3E-06	NFPA 805		5.2E-05	5.8E-05	GI-199	3.0E-06
2	4.3E-06		0.55	2.4E-06		5.7	2.5E-05	3.1E-05	GI-199	2.7E-05
2	2.7E-06		0.55	1.5E-06		5.7	1.5E-05	1.9E-05	GI-199	4.6E-05
2	1.4E-05		0.55	7.7E-06		5.7	8.0E-05	1.0E-04	GI-199	5.1E-05
2	8.4E-06		0.55	4.6E-06		5.7	4.8E-05	6.1E-05	GI-199	6.3E-06
2	2.8E-06	SPAR-EE		5.0E-05	SPAR-EE		5.3E-06	5.9E-05	GI-199	5.7E-06
2	1.9E-06		0.55	1.0E-06		5.7	1.1E-05	1.4E-05	GI-199	1.3E-05
2	1.7E-06	SPAR-EE		1.0E-08	NFPA 805		7.3E-05	7.5E-05	GI-199	1.0E-05
2	3.1E-05		0.55	1.7E-05		5.7	1.8E-04	2.2E-04	GI-199	7.1E-06

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[4] The values in this table are considered representative of each because they were generated from an NRC SPARE model for that plant and used other referenced inputs as noted in the text. The tabulated values may not reflect the licensee's own PRA analysis based on their most current models.

Results

The scoping estimates of multiunit nuclear power plant site ILCFRs are lower than the per-unit ILCFR QHO of 2×10^{-6}/y, as shown at the bottom of Table 3. These scoping estimates are subject to the following assumptions and limitations:

1. The consequences of a multiunit accident are proportional to the number of units involved. The results of informal staff calculations indicate that, with respect to health-related consequences, multiunit risk is subadditive. As a result, this assumption is conservative.

2. The contribution from SUIs includes internal initiating events, internal floods, and internal fires. Due to the limited amount of information about internal flood and internal fire CDFs, 80th percentile multipliers were developed from the available information. Other types of SUIs are not included in the analysis.

3. The contribution from CCIs includes seismic events and tornados. Other types of CCIs are not included in the analysis.

4. The CPLCF for all types of accidents at all locations is 10^{-3}. This value is at the upper range of CPLCF estimates from previous accident consequence studies.

5. The scoping estimates only consider the situation when all of the units at a multiunit site are operating. Shutdown and low-power modes are not included in the analysis.

6. The scoping estimates do not include the risk from accidents involving the spent fuel pool or dry storage casks.