SCOPING ESTIMATES OF MULTIUNIT ACCIDENT RISK

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Abstract: Many nuclear power plants (NPPs) are co-located at a single site. Although NRC regulations recognize the potential for multiunit accidents, probabilistic risk assessments of NPPs have mainly focused on estimating the risk of a single NPP. This paper develops a scoping approach for estimating the total multiunit site risk that uses information from a single-unit Level 3 probabilistic risk assessment.

Keywords: multiunit risk, site risk, accident risk, PRA

1. INTRODUCTION

The Nuclear Regulatory Commission (NRC) and its predecessor, the Atomic Energy Commission (AEC), have long been concerned about the risk of accidents that affect multiple units (reactors) located at a common site. NRC regulations [1] limit the sharing of systems, structures and components important to safety 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. In addition, NRC regulations [2] provide requirements for determining the exclusion area, the low population zone, and the population center distance for multiunit sites. Following the accident at Three Mile Island in 1979, the NRC considered the need to establish additional regulations to reduce the likelihood and consequences of multiunit accidents [3]. The subject of multiunit risk was considered during development of the Commission's Safety Goal Policy Statement [4], which was issued in 1986. During the State-of-the-Art Reactor Consequence Analysis (SOARCA) project [5], completed in 2012, a potential Generic Issue was identified concerning the likelihood and consequences of multiunit accidents. In 2012, the NRC's Office of New Reactors established a Working Group to consider how to address the risk of accidents that affect small modular reactors (SMRs) in the design certification and combined operating licensing processes. The 2011 accident at Fukushima Dai-ichi in Japan has re-emphasized the fact that multiunit accidents can happen, and that it is important to understand their risks.

This paper presents an approach for using the results of a single-unit Level 3 probabilistic risk assessment (PRA) to develop a scoping estimate of the total site risk due to accidents that affect one or more reactors located at a common site.

2. 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.,

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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.

2.1. 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.

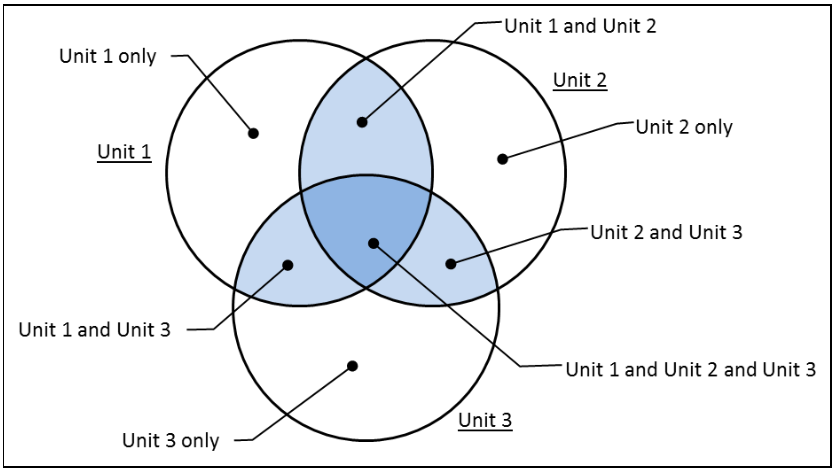

Figure 1. Venn Diagram Depicting Multiunit Accidents.

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:

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

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

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

2.2. 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:

$$\begin{aligned} U1 &= \text{release from Unit 1} \\ U2 &= \text{release from Unit 2} \\ U3 &= \text{release from Unit 3} \end{aligned} \quad (4)$$

From these fundamental definitions, define the following compound events:

$$\begin{aligned} U1 \cap \overline{U2} \cap \overline{U3} &= \text{release from only Unit 1} \\ \overline{U1} \cap U2 \cap \overline{U3} &= \text{release from only Unit 2} \\ \overline{U1} \cap \overline{U2} \cap U3 &= \text{release from only Unit 3} \\ U1 \cap U2 \cap \overline{U3} &= \text{release from only Unit 1 and Unit 2} \\ U1 \cap \overline{U2} \cap U3 &= \text{release from only Unit 1 and Unit 3} \\ \overline{U1} \cap U2 \cap U3 &= \text{release from only Unit 2 and Unit 3} \\ U1 \cap U2 \cap U3 &= \text{release from Unit 1, Unit 2 and Unit 3} \end{aligned} \quad (5)$$

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:

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

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

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

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†:

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

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:

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

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.

2.3. 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

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

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*.

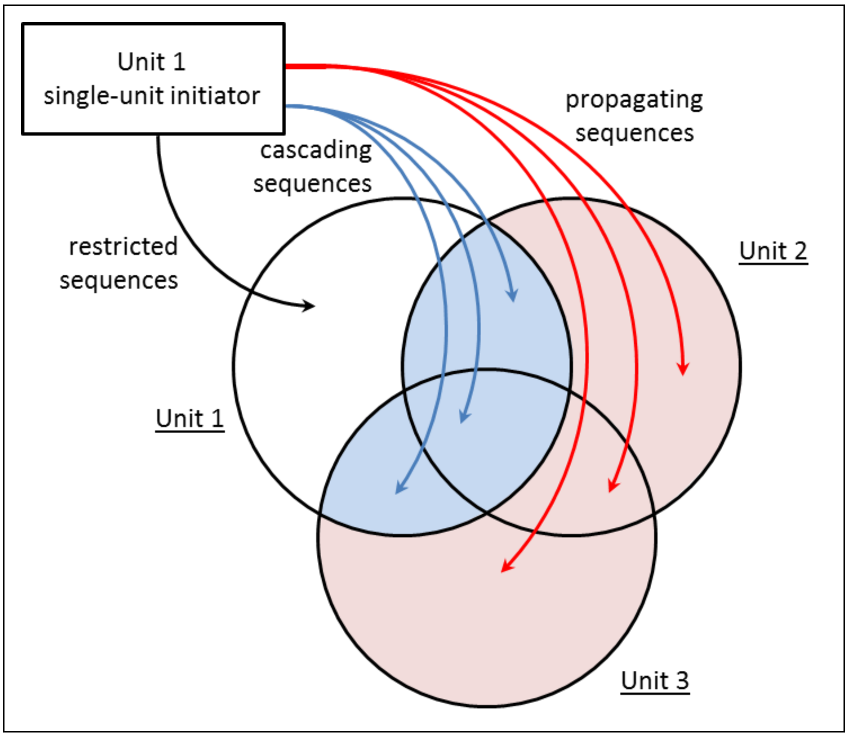

Figure 2. Restricted, Cascading, and Propagating Sequences Caused by a Single-Unit Initiator.

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

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

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:

$$\begin{array}{lll} R^{(n)}_{S,SUI} & = & \text{site risk due to } SUIs \\ n & = & \text{number of identical units at the site} \\ f_{SUI} & = & \text{frequency of } SUIs \\ p^{(n)}_{k,SUI} & = & \Pr\{\text{release from exactly } k \text{ of } n \text{ units due to restricted and cascading sequences} \mid SUI\} \\ q^{(n)}_{k,SUI} & = & \Pr\{\text{release from exactly } k \text{ of } n \text{ units due to propagating sequences} \mid SUI\} \\ C^{(n)}_{k,SUI} & = & \text{consequence due to release from exactly } k \text{ of } n \text{ units after } SUI \end{array} \quad (14)$$

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

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

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:

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

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:

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

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):

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

2.4. 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 causes 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.

3. Example Scoping Site Risk Estimates

The results of NUREG-1150 can be used to demonstrate the approach. Noting that seismic events are CCIs, and internal events and internal fires are SUIs, bounds on total site risk are shown in Tables 1 and 2 below:

Table 1: Example Scoping Site Risk Estimates Based on NUREG-1150

Individual Early Fatality Risk (0-1 miles)					
	CCIs	SUIs			Bounding Site Risk
Plant	Seismic $R_{\text{single-unit},CCI}$	Internal Events	Internal Fires	Total $R_{\text{single-unit},SUI}$	$R_S^{(2)}$
Peach Bottom	1.6E-6/ry[a]	4.7E-11/ry	4.8E-10/ry	5.3E-10/ry	3.2E-6/sy[b]
Surry	1.8E-7/ry	1.6E-8/ry	6.3E-10/ry	1.7E-8/ry	4.3E-7/sy
Individual Latent Cancer Fatality Risk (0-10 miles)					
	CCIs	SUIs			Bounding Site Risk
Plant	Seismic $R_{\text{single-unit},CCI}$	Internal Events	Internal Fires	Total $R_{\text{single-unit},SUI}$	$R_S^{(2)}$
Peach Bottom	1.6E-6/ry	4.3E-10/ry	2.4E-9/ry	2.8E-9/ry	3.2E-6/sy
Surry	3.1E-8/ry	1.7E-9/ry	1.2E-10/ry	1.8E-9/ry	6.9E-8/sy

[a]ry = reactor-year
[b]sy = site-year

Sources:
Peach Bottom [6], Tables 5.1-1, 5.1-2 and 5.1-3
Surry [7], Tables 5.1-1, 5.2-1 and 5.3-1

For both sites, the CCIs (seismic events) are, by far, the largest contributors to the bounding site risk estimates. As a result, within the assumptions of the scoping model, the bounding site risk should be a reasonably close approximation to the actual site risk because the bounding approximation involves the contribution from SUIs.

4. LIMITATIONS OF THE APPROACH

The scoping model of multiunit accident risk that is developed in this paper assumes that all of the units at a site are identical. In reality, however, the individual units at a multiunit site are often asymmetrical. For example, consider a two-unit site that has two emergency diesel generators for each unit and a fifth “swing” emergency diesel generator that can be aligned to either unit. Use of the results of a single-unit PRA that credits use of the swing diesel will underestimate the total multiunit risk (because there are not two swing emergency diesel generators, as implied by the assumption) whereas ignoring the swing diesel altogether overestimates the total site risk. This type of asymmetry may not be important if the site risk is mainly due to CCIs.

Another consideration is co-located sites. In the U.S., the FitzPatrick site (consisting of a single unit) is co-located with the Nine Mile Point site (consisting of two units); similarly, the Hope Creek site (consisting of a single unit) is co-located with the Salem site (consisting of two units). In such cases, CCIs such as seismic events could potentially affect all three units at the co-located sites. However, the simplified approach taken in this paper is not adequate for fully understanding the impact of SUIs on these types of co-located sites.

The simplified approach taken in this paper is not adequate for estimating the total site risk due to all radiological sources (reactor and spent fuel), again because these sources are not identical and have different types of initiating events and resulting accident sequences.

5. CONCLUSIONS

1. Site risk estimates should include the contribution from common-cause initiators (CCIs) and single-unit initiators (SUIs), which can lead to cascading, propagating or restricted accident sequences.

2. It is possible to determine an upper bound on the risk of a site that has an arbitrary number of identical units using the results of a single-unit PRA. Specifically:

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

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