Introduction

Recent regulatory movement with respect to PSA is “integrated site risk”.
- NSC Performance Goals issued in July 2006 require that the effects of multiple nuclear power plants in a site should be considered to meet the safety goals of CDF and CFF.
- Draft alternative of 10CFR 50 for new reactor plants requires assessment of integrated site risk in addition to individual reactor risks to meet the US NRC’s QHO.
- External events, especially earthquakes, may cause simultaneous multiple nuclear reactor damages in a site.
- To assess integrated site risks, seismic PSA method for multi-unit sites: CORAL-reef code has been developed
- The essential models and some sample analyses are presented.

Seismic PSA Method for Multi-Unit Sites

- Maximum units in a site is 8 in the world and 7 in Japan. To make it practical, tactful and efficient, to analyze up to 9 units simultaneously, following strategy is adopted.
  - It is known from detailed seismic PSAs that a limited number of dominant or key structures, equipment and accident sequences dominate the results. Those key elements are simulated and the others may be lumped together as non-dominant residues.
  - Reactors are grouped by the similarity of design and architectures.

<table>
<thead>
<tr>
<th>Detailed or screening Seismic PSA for representing plants in a site</th>
<th>DATA</th>
</tr>
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<tr>
<td>Seismic PSA Method for Multi-Unit Site</td>
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<table>
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<tr>
<th>Important SCC, Dominant Sequences Other Risk Insights</th>
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<tr>
<td>Seismic PSA Method for Multi-Unit Site</td>
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Dominant Contributors by Risk Reduction Potential (Surry plant for NUREG-1150)

<table>
<thead>
<tr>
<th>Dominant Contributors Ranked by Risk Reduction Potential</th>
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<tbody>
<tr>
<td>Ceramic Insulators                               50%</td>
</tr>
<tr>
<td>4KV Busses-1H                                    36%</td>
</tr>
<tr>
<td>4KV Busses-1J                                    36%</td>
</tr>
<tr>
<td>Condensate Storage Tank                          26%</td>
</tr>
<tr>
<td>Diesel Generator 1-failure to start               22%</td>
</tr>
<tr>
<td>Diesel Generator 3-failure to start               22%</td>
</tr>
<tr>
<td>Refueling Water Storage Tank                      21%</td>
</tr>
<tr>
<td>480V MCC-1H                                      9%</td>
</tr>
<tr>
<td>480V MCC-1J                                      9%</td>
</tr>
<tr>
<td>Auxiliary Feed-water –XCONN                        3%</td>
</tr>
<tr>
<td>OEP-DG-3U2                                       3%</td>
</tr>
<tr>
<td>Other basic events                                &lt;1% each</td>
</tr>
</tbody>
</table>
Dominant Accident Sequences in order of Importance (Surry plant for NUREG-1150)

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Description</th>
<th>Probability</th>
</tr>
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<tbody>
<tr>
<td>T1-6</td>
<td>(LOSP with Loss of Cooling)</td>
<td>40%</td>
</tr>
<tr>
<td>T1-1</td>
<td>(LOSP leading to Seal LOCA)</td>
<td>27%</td>
</tr>
<tr>
<td>T3-1</td>
<td>(Transient leading to Seal LOCA)</td>
<td>8%</td>
</tr>
<tr>
<td>SLOCA-7</td>
<td>(Small LOCA with failure of HPSI)</td>
<td>5%</td>
</tr>
<tr>
<td>T1-5</td>
<td>(LOSP with F&amp;B and AFWS failures)</td>
<td>5%</td>
</tr>
<tr>
<td>T3-6</td>
<td>(Transient with Loss of Cooling)</td>
<td>3%</td>
</tr>
<tr>
<td>ALOCA-3</td>
<td>(Large LOCA with failure of LPI)</td>
<td>3%</td>
</tr>
</tbody>
</table>

Essential Models and Outputs

- **Models**
  - Monte Carlo approach for up to 9 units in max. 3 groups. Point Estimate and Uncertainty Analysis can be performed.
Monte Carlo Multivariate Correlation

- Basic equations for correlation analysis by Monte Carlo approach are developed that compute correlated failures of structures and components for zero-partial-complete, in series/parallel, and inside/across units

\[
S_j = \beta_i \left[ R_{ij} \rho_{ij} + R_i \sqrt{1 - \sum \rho_{ij}} \right] \quad ------- (1)
\]

Verification of Correlation Equations

- Correlation equations can be verified by the formula:
  \[
  \rho_{ij} = \frac{\text{Co-variance}(S_i, S_j)}{\sqrt{\text{Var}(S_i) \text{Var}(S_j)}} , \quad \rho_{ii} = \text{Var}(S_i)
  \]

- Sensitivity analysis on sampling numbers (by CORAL-reef):
Rules for Assigning Response Correlation

1. Components on the same floor slab, and sensitive to the same spectral frequency range (i.e. ZPA, 5 to 10 Hz, or 10 to 15Hz) will be assigned response correlation = 1.0
2. Components on the same floor slab, and sensitive to different ranges of spectral acceleration will be assigned response correlation = 0.5
3. Components on different slabs (but the same building) and sensitive to the same spectral frequency ranges (ZPA 5 to 10 Hz or 10 to 15Hz) will be assigned response correlation = 0.75
4. Components on the ground surface (outside tanks, etc.) shall be treated as if they were on the grade floor of an adjacent building.
5. “Ganged” valve configurations (either parallel or series) will have response correlation = 1.0
6. All other configurations will have response correlation equal to zero.

Asymmetric Probability Distribution of Seismic Hazard Uncertainty

Asymmetric probability distribution of seismic hazard uncertainty is presented by 4 log-normal distributions:

![Asymmetric Probability Distribution](image-url)
Sample Analysis 1

Probability of Simultaneous Core Damages in 5-unit Site

Monte Carlo Runs (1000 x 500 runs/GPA)
Number of Simultaneously Damaged Plants
95% probability = 2.47 plants (49%)
Mean = 1.66 plants (33%)
5% probability = 1.22 plants (24%)

X: Point Analysis = 1.58 plants (32%)

Results:
1) Mean number of plants with core damage is 1.66 out of 5
2) Site CDF/site-year is about 3 times mean CDF/reactor-year

Sample Analysis 2

Uncertainty Analysis of CDF
Level-2 PSA Analysis Models

- Seismic Level-2 PSA by Monte Carlo method can be performed at the same time with Level-1 PSA for up to 9 units in a site
- LERF (short-term), CFF (long-term) and source terms for radioactive release categories for individual units (1/ry) and integrated site (1/site-year) for all the patterns of unit failure combination, e.g. 32 patterns of combination 5 unit-site.
- Containment failure event tree:

```
 a  β  ?  d  e
```

Not failed

- CR-VSE: Containment Rupture --- Vessel Steam Explosion
- CL: Containment Leakage
- CR-B: Containment Rupture --- Burning
- CR-OP: Containment Rupture --- Overpressure
- CR-MT: Containment Rupture --- Melt-through

Sample Analysis 3

Seismic Accident Management: **Mutual Support** by Tying between Units

![Event Tree Diagram](image.png)
Effects of Mutual Support in Multi-Unit Site

- Tying risk-dominant components within a safety functional system is effective.
  

- Sample Analysis shows effect of 50% reduction in site CDF

Risk Metrics for Integrated Site Safety

- Current safety regulation and PSA are based on individual reactor safety in the term of per reactor-year
- However it is not reasonable that intact reactors just looking at damaged reactors without any help in a site.
- New regulatory framework would require consideration of integrated site risks.
- Independence is important to maintain high reliability in design and operation; on the other hand, mutual support accident management is recommended strongly for enhancement of seismic safety of NPP.
- Emergency planning should take consideration of multiple reactor failures by earthquakes
- PSA technology for multiple nuclear reactors will be necessary as a state of art PSA. The technology will be dispensable for developing next generation fleets of modular-type small reactors.
## Risk Metrics for Integrated Site Safety

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<tr>
<th>Integrated Site Metric</th>
<th>Definition</th>
<th>Remarks</th>
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<tr>
<td>Integrated Site Reactor Damage</td>
<td>Integrated Site CDF, LERF, CFF, Source-term</td>
<td>Unit is 1/site year</td>
</tr>
<tr>
<td>Site Risk Factor</td>
<td>$\alpha$</td>
<td>$1 \leq \alpha \leq N$</td>
</tr>
</tbody>
</table>

### Integrated Site Reactor Damage

$\text{Integrated Site Reactor Damage} = \text{Integrated Site CDF, LERF, CFF, Source-term}$

### Site Risk Factor

$\alpha = \frac{\text{Number of Reactor Damages}}{\text{Number of Reactor Year}}$

### Mean number of simultaneous Reactor Damages

$\bar{n} = \frac{\text{Number of Reactors}}{\text{Number of Reactor Year}}$

### Site Risk Conservation Criteria

$\alpha = \frac{\text{Number of Reactor Damages}}{\text{Number of Reactor Year}}$

### Multi-unit site effect factor

$\gamma = \frac{\text{Multi-unit site effect (Plus):} \ \gamma \ < 1}{\text{Multi-unit site effect (Minus):} \ \gamma \ > 1}$

### Conclusion

- New regulatory framework tends to require integrated site risk assessment to meet safety goals.
- Seismic PSA methodology for multi-unit site “CORAL-reef” has been developed. There still remains needs of further developments, such as correlation data, Level 3 PSA.
- Increase in site risks due to increased number of reactors in a site may be compensated to a some extent by multi-unit PSA and accident management by mutual support.
- Site integrated CSD / LERF/ CFF per site-year are desired to be assessed in addition to per reactor-year to enhance real risks for nuclear sites.
- Seismic PSA method for multi-unit sites will be useful for current reactors and next generation reactors, including fleets of future advanced modular-type small reactors.
END
Thank you for your attention