Next Generation PSA Software
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Seismic PSA Method for Multi-Unit Site---CORAL-reef

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Introduction

Recent regulatory movement with respect to PSA is "integrated site risk".

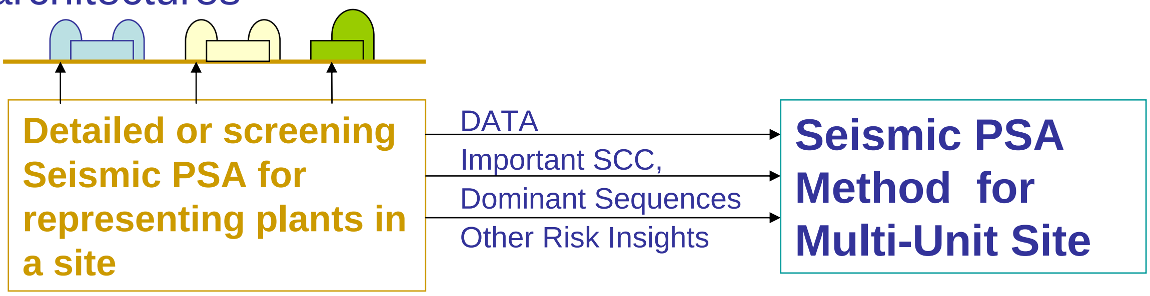
- NSC Performance Goals issued in July 2006 require that the effects of multiple nuclear power plants in a site should be considered to meet the safety goals of CDF and CFF.
- Draft alternative of 10CFR 50 for new reactor plants requires assessment of integrated site risk in addition to individual reactor 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.

Reference: Paper published in UK magazine of Reliability Engineering & System Safety, Vol.92, No.7, July 2007, 883-894

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



Dominant Contributors by Risk Reduction Potential (Surry plant for NUREG-1150)

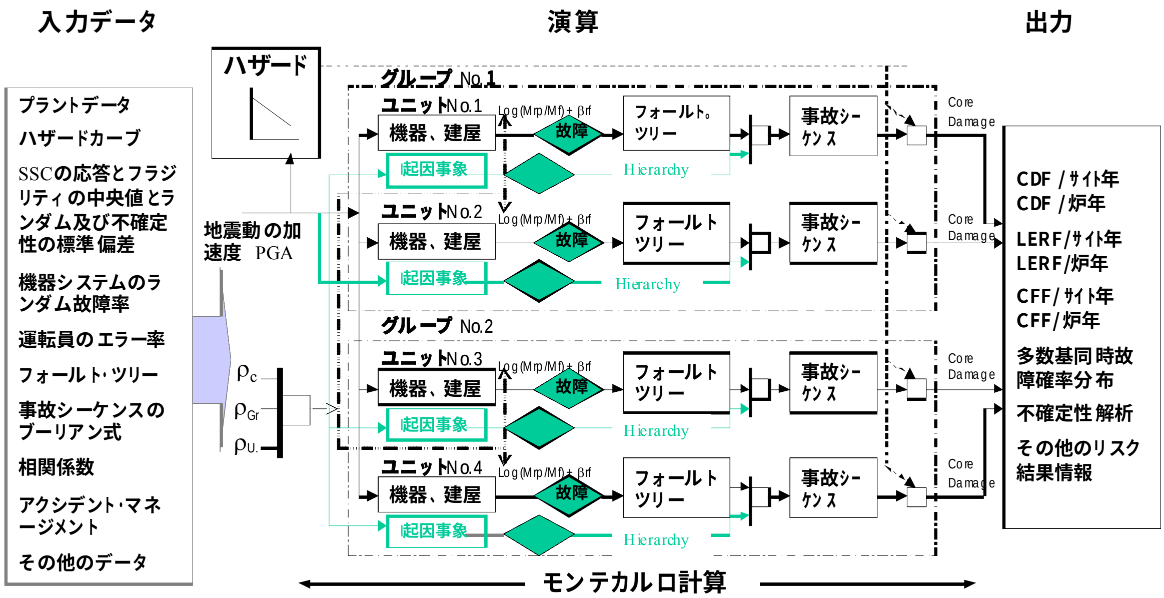
Dominant Contributors Ranked by Risk Reduction Potential	
Ceramic Insulators	50%
4KV Busses-1H	36%
4KV Busses-1J	
Condensate Storage Tank	26%
Diesel Generator 1-failure to start	22%
Diesel Generator 3-failure to start	
Refueling Water Storage Tank	21%
480V MCC-1H	9%
480V MCC-1J	
Auxiliary Feed-water –XCONN	3%
OEP-DG-3U2	3%
Other basic events	<1% each

Dominant Accident Sequences in order of Importance (Surry plant for NUREG-1150)

Dominant Accident Sequences in order of importance		
T1-6	(LOSP with Loss of Cooling)	40%
T1-1	(LOSP leading to Seal LOCA)	27%
T3-1	(Transient leading to Seal LOCA)	8%
SLOCA-7	(Small LOCA with failure of HPSI)	5%
T1-5	(LOSP with F&B and AFWS failures)	5%
T3-6	(Transient with Loss of Cooling)	3%
ALOCA-3	(Large LOCA with failure of LPI)	3%

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

$$S_i = \beta_i \left[R_{Cij} \sqrt{\rho_{ij}} + R_i \sqrt{1 - \Sigma\rho_{ij}} \right] \quad \text{------ (1)}$$

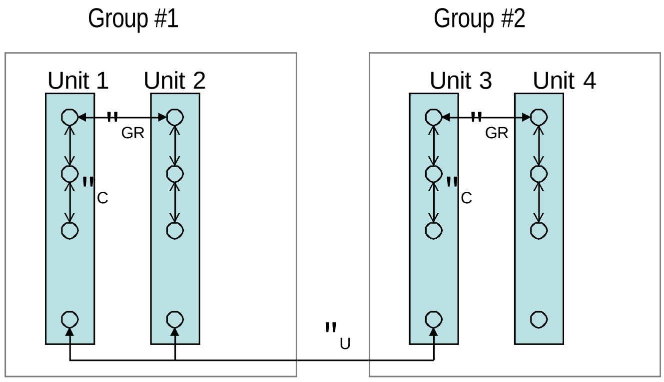
Response, Fragility deviations (S_i)

Uncertainty Standard Deviation (β_i)

Random Number common to i, j (R_{Cij})

Correlation Coefficient (ρ_{ij})

Random Number for each component i, j (R_i)

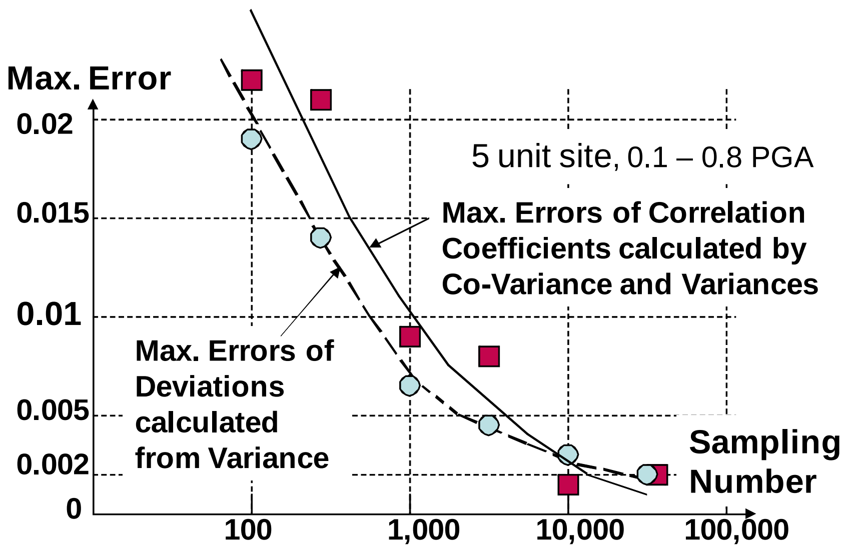


Verification of Correlation Equations

- Correlation equations can be verified by the formula:

ρ_{ij} = Co-variance(S_i,S_j) / $\sqrt{Var(S_i)Var(S_j)}$, β_i^2 = Var(S_i)

- Sensitivity analysis on sampling numbers (by CORAL-reef):



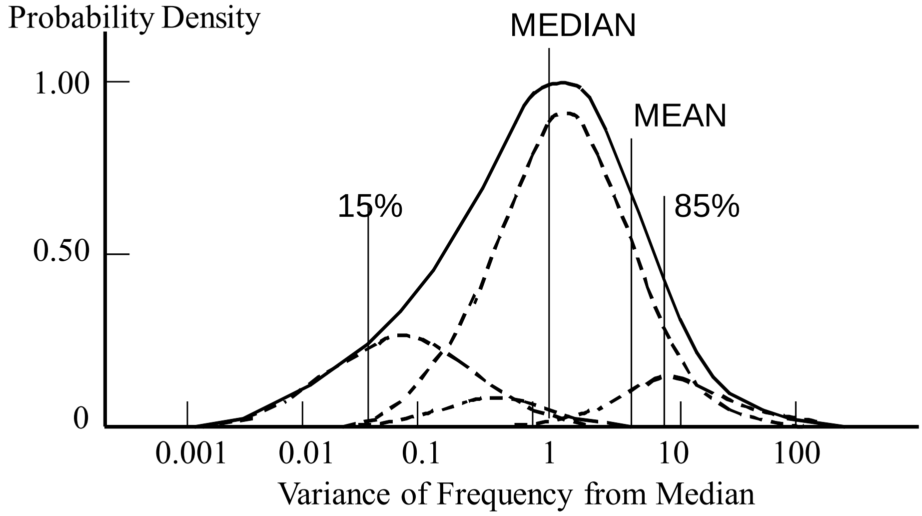
Rules for Assigning Response Correlation

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.

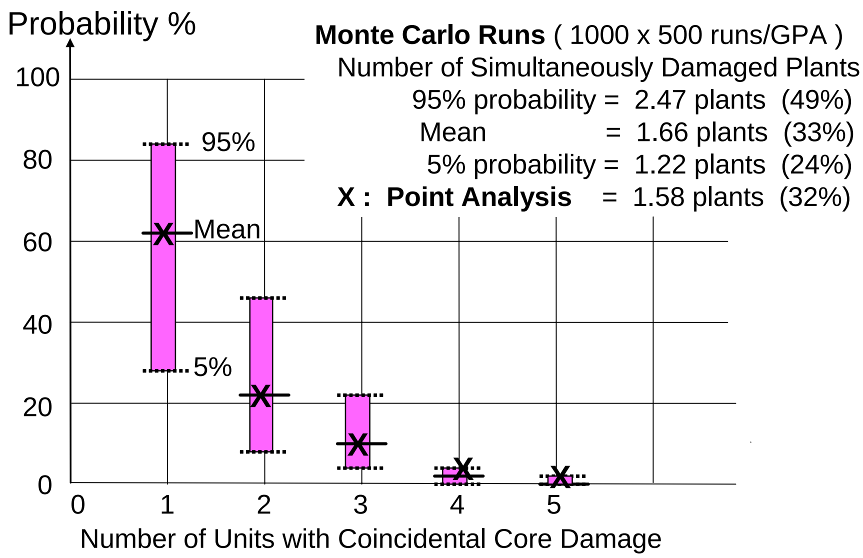
Asymmetric Probability Distribution of Seismic Hazard Uncertainty

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



Sample Analysis 1

Probability of Simultaneous Core Damages in 5-unit Site



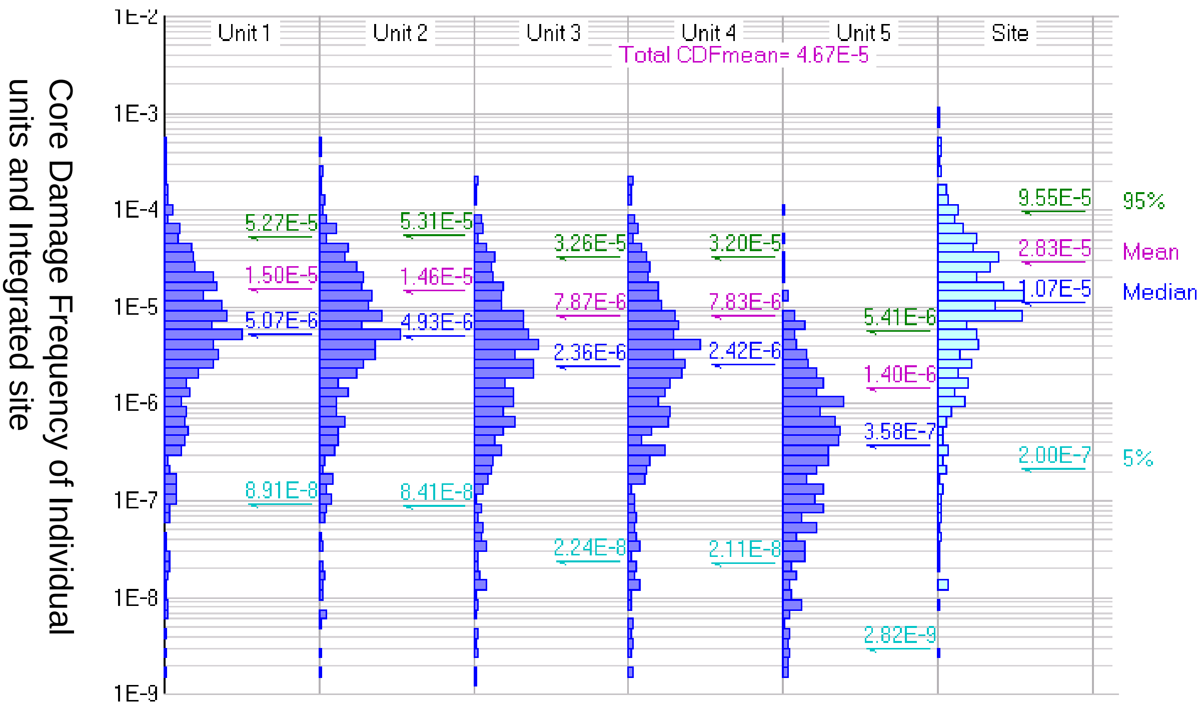
Results:

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

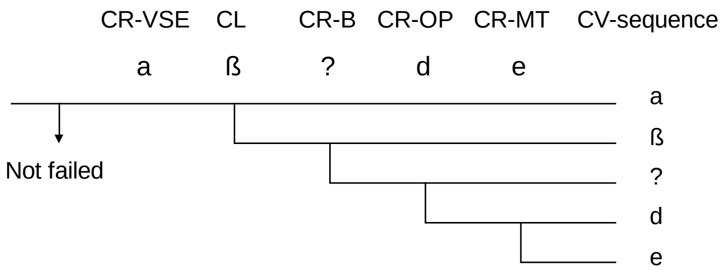
Sample Analysis 2

Uncertainty Analysis of CDF



Level-2 PSA Analysis Models

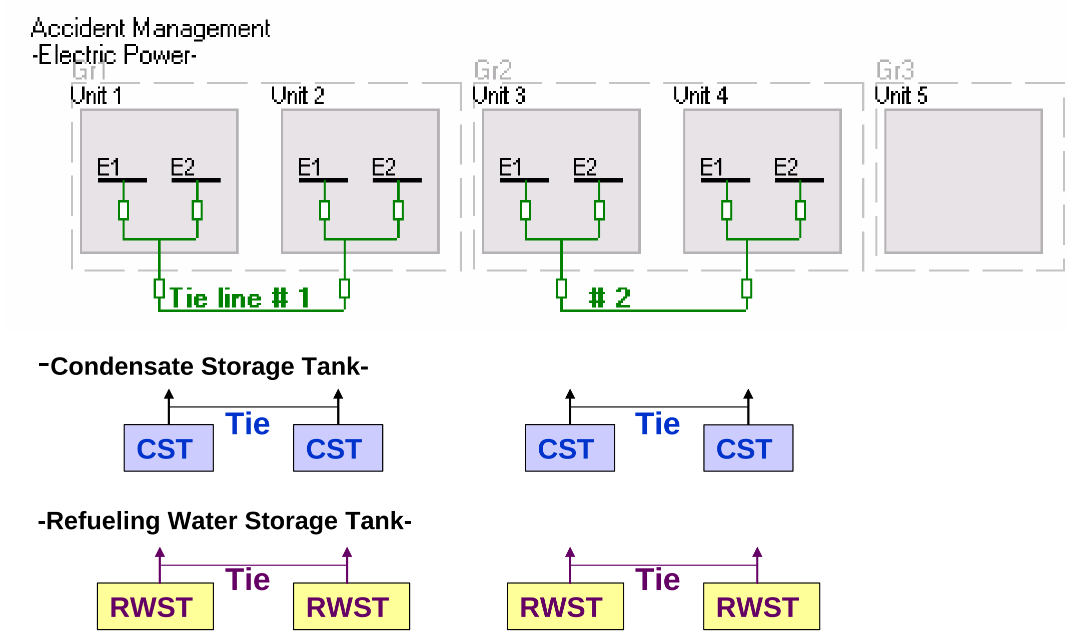
- Seismic Level-2 PSA by Monte Carlo method can be performed at the same time with Level-1 PSA for up to 9 units in a site
- LERF (short-term) , CFF(long-term) and souse terms for radioactive release categories for individual units (1/ry) and integrated site (1/site-year) for all the patterns of unit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



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

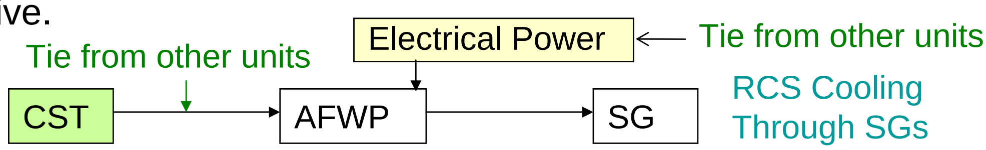
Sample Analysis 3

Seismic Accident Management: Mutual Support by Tying between Units

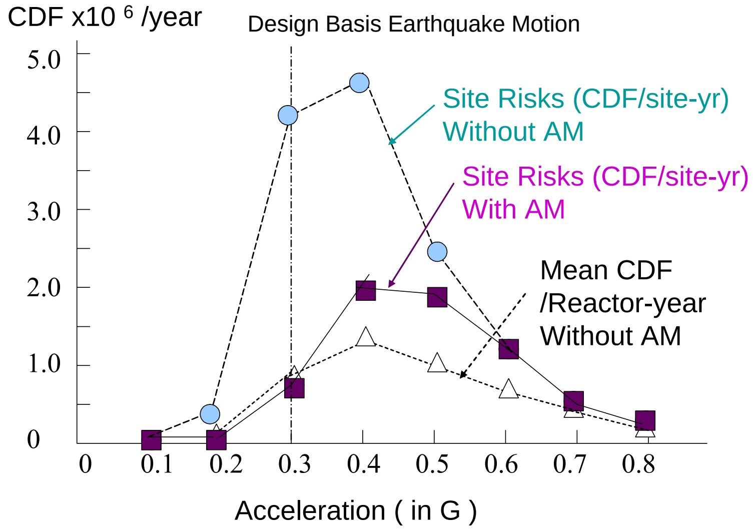


Effects of Mutual Support in Multi-Unit Site

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



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



Effect of AM:

CDF/site / mean CDF/ry

η= N x 1/λ x AM = **1.3**

5 **1/1.9** **0.5**

where,

N=number of units (5),

λ=mean number of damaged units (1.9)

Multi-Unit Site Effect Factor

η λ/N =**多数基効果=** 0.49

Note: Terminology is tentative

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

Integrated Site Metrix **サイト総合指標**	Definition **定　義**	Remarks **備　考**
Integrated Site Reactor Damage **サイト総合原子炉損傷**	Integrated Site CDF, LERF, CFF, Source-term **サイト**CDF, LERF, CFF, **ソースターム**	**単位は 1/サイト年**
Site Risk Factor **サイトリスク比**	? = Integrated Site CDF (/site·y) / Mean CDF in site (/ry) ? = サイトCDF (/サイト年) / サイト平均CDF (/炉年)	1 ≤ ? ≤ N N＝Number of units **原子炉基数**
Mean number of simultaneous Reactor Damages **同時原子炉損傷平均基数**	? = Σ n ? p(n) / Σ p(n) n = 1 ～ N (**原子炉基数**)	n = Number of Simultaneous Reactor Damages **同時損傷の原子炉基数** p(n) = Probability of n n**基同時損傷の確率**
Site Risk Conservation Criteria **サイトリスク保存則**	??? ＝ N	Total site risks is conserved, if unit inter-relations are only correlation **原子炉間の関連が相関のみの場合には、サイトリスクは保存される**
Multi-unit site effect factor ? **多数基効果指標**	? = ??? / N =**サイトリスク比** x **平均同時損傷 / 全基数** or ? = N / ??	Multi-unit site effect (Plus): ? < 1 **サイトリスク減 (相互支援等)** Multi-unit site effect (minus) : ? > 1 **サイトリスク増 (マイナス効果)**

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