EARTHQUAKES, SAFETY GOALS, AND MULTI-UNITS (OH MY)

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Earthquakes, safety goals, and their impact on multi-units are the subject for the panel discussion, “"Extreme External Events, Site Risk Management and Safety Goals". This short paper outlines my opinions. My conclusions are:

1. *Actual earthquake data should be used to understand real-world successes and failures of SSCs with respect to actual ground motion records and DIPs.*
2. *Instead of desperately trying to meet QHO surrogate goals such as CDF, LERF, and now LRF, rigorous Level 2 and Level 3 PRAs should be required.*
3. *Approaches such as CORAL-Reef an iterative approach should be used immediately on multi-unit sites, the results examined, improvements made, and then calculated again.*

I. EARTHQUAKES

Actual earthquake data, when compared with calculated hazard curves and fragility analyses, often do not agree. For example, a cumulative absolute velocity (CAV) of 2.8 was thought to be high enough to cause damage to safety systems at nuclear power plants. However, the Great Eastern Japan Earthquake caused a free-field CAV of 8.3 in the NS direction at the Onagawa NPS with no damage to safety systems.

We have several measures of earthquake intensity which we try to use as the silver bullet of damage indicating parameters (DIPs):

- PGA
- Max SA
- Response Spectra
- CAV
- Shindo (IJMA)
- Arias

To understand which DIPs, under what conditions including distance from fault, soil structure, elevation, etc., are the best indicators means that we must create an up-to-date industry database, the EPRI SQUG database notwithstanding, that includes both SSC successes and failures.

It must be a threaded database which links:

- an earthquake catalog;
- strong motion records;
- site information, like soil structure, distance from a fault …;
- and structure, system, and component success and failures.

Only in this way can we make proper judgments about which measures to use in a specific NPP location.

And we must use Bayes’ Theorem to update fragilities with earthquake data.

II. SAFETY GOALS

Where do the quantitative safety goals for CDF or LERF come from? The CDF goal was derived by working backward from the qualitative health objective (QHO) for cancers. This was achieved by using rough numbers of containment performance from PRAs available at that time.

For the 1980 ACRS safety goals studies, the ACRS started with setting the goal as the likelihood of death to 0.1% of the chance of observed cancer deaths in the population. That gets you to about 1e-7. Then backing up to release and CDF, you can get to 1e-4.

Now, that was in the late 1970s. Since then, most recognize that 1e-4 is a poor metric if public health is the ultimate concern, for western reactors.

This was then sourced to the NRC safety goal policy which presents 1e-4 as a "subsidiary safety objective" following an explicit statement of the rational:

> *"The risk to the population in the area of nuclear power plant of cancer fatalities that might result from nuclear power plant operation should not exceed one-tenth of one percent (0.1%) of the sum of cancer fatality risks resulting from all other causes."*[1]

There are some background studies from Level 3 PRAs that showed way back when that if you keep your CDF below 1e-4 you are fairly certain to meet the QHOs for latent health effects, and if you keep your LERF below 1e-5 you are fairly certain to meet the QHOs for early health effects. These things were established before we determined that the source terms that we used to use are much higher than what is believed today. All this is done with a "one-reactor-at-a-time" mindset, as none of these background studies considered multi-unit accidents.

The reason this becomes important, especially when considering earthquakes, is that in many PRAs, our peer reviews are showing us that attaining the CDF goal of 1e-5 and the LERF goal of 1e-6 present difficulties, if one includes earthquakes and tsunami, without questionable screening, assumptions, and human action credits.

But maybe if Level 2 and 3 PRAs were regularly done, we would find that attaining the QHOs would be possible even if CDF and LERF quantitative goals were not met and even if earthquakes or tsunami were included. Moreover, since Fukushima, many regulators have changed their safety goals by a factor of ten to 1e-5 for CDF and 1e-6 for LERF, without any consideration or studies of what this practically means for health risk to the public.

I also want to remark here that it may be beyond our ability to honestly attain safety goals for CDF (1e-5) and LERF (1e-6), respectively 1/100,000 years and 1/1,000,000 years, when one considers our (lack of) knowledge about the recurrence frequencies of extreme earthquakes, tsunami, and other natural hazards. We only have earthquake instrument data for about 100 years.

Of course, multi-unit considerations are another kettle of fish

III. MULTI-UNITS

Even before the Fukushima disaster, the then Japanese regulator, the Nuclear Safety Commission (NSC) issued performance goals in July 2006 that require that the effects of multiple nuclear power plants in a site should be considered to meet the safety goals of CDF and CFF. Around the same time, the US NRC issued a draft alternative of 10CFR 50 for new reactors required the assessment of integrated site risk in addition to individual reactor risks to meet the US NRC's QHO. Of course, external events, especially earthquakes and tsunami, may cause simultaneous multiple nuclear reactor damage to a site.

Dr. Tadakuni Hakata, a former member of the NSC and a seismic PRA expert invented a seismic PRA method and accompanying software to assess integrated site risks for multi-unit sites: CORAL-Reef. Dr, Hakata was a friend a colleague for many of us in the PRA community. Dr. Hakata died in 2014.

Unfortunately for the PRA community, Dr. Hakata's work has been largely ignored. I would like to remedy this. Here, I will outline his key observations and during the panel session, I will show some of his original presentation.

Dr. Hakata focused on creating a seismic PRA method and software for multi-unit sites.[2] At that time, the maximum number of units on a site was eight worldwide and seven in Japan. To make the software practical and efficient, and to analyze up to 9 units simultaneously, the following strategy was adopted:

1. It is known from detailed seismic PRAs that a limited number of dominant or key SSCs and accident sequences dominate the results.
2. Those dominant elements are evaluated using a Monte Carlo simulation.
3. the non-dominant SSCs and sequences are lumped together as non-dominant residues.
4. Reactors on the same site are grouped by the similarity of design and architectures.

CORAL-Reef's Monte Carlo approach can handle up to 9 units in a maximum of three separate groups. Both point estimate and uncertainty analysis can be performed. The method can be applied to Level 1 and Level 2 PRAs. For multivariate correlation, basic equations for correlation analysis by Monte Carlo can be developed to compute correlated failures of SSCs for zero-partial-complete, in series/parallel, and inside/across units.

Dr. Hakata's correlation rules are straight forward:

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.

Dr. Hakata did a study of a five-unit site with a double loop Monte Carlo simulation of 1000 outer runs and 500 inner runs per GPA. The probability of simultaneous core damage to the five units result was:

- 95% probability = 2.47 units (49%)
- Mean = 1.66 plants (33%)
- 5% probability = 1.22 plants (24%)
- Point Analysis = 1.58 plants (32%)

The site CDF/reactor-year was about 3 times the unit CDF/reactor-year.

IV. CONCLUSION: OH MY

My conclusions are simple:

4. Actual earthquake data should be used to understand real-world successes and failures of SSCs with respect to actual ground motion records and DIPs.
5. Instead of desperately trying to meet QHO surrogate goals such as CDF, LERF, and now LRF, rigorous Level 2 and Level 3 PRAs should be required.
6. Approaches such as CORAL-Reef an iterative approach should be used immediately on multi-unit sites, the results examined, improvements made, and then calculated again.

ACKNOWLEDGMENTS

Thank you to (alphabetically) George Apostolakis, Tadakuni Hakata, Karl Fleming, David Johnson, Nathan Siu, and John Stetkar.

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