Transactions, **SMiRT-26**
Berlin/Potsdam, Germany, July 10-15, 2022
Division VII

LOSS OF OFFSITE POWER SEISMIC FRAGILITY GUIDANCE

Riccardo Cappa[1], Frederic F. Grant[2], Greg S. Hardy[3], and John Richards[4]

[1] Consulting Engineer, Simpson Gumpertz & Heger Inc., Newport Beach, CA, USA (rcappa@sgh.com)
[2] Associate Principal, Simpson Gumpertz & Heger Inc., Newport Beach, CA, USA (ffgrant@sgh.com)
[3] Senior Principal, Simpson Gumpertz & Heger Inc., Newport Beach, CA, USA (gshardy@sgh.com)
[4] Senior Technical Executive, Electric Power Research Institute, Charlotte, NC, USA (jrichards@epri.com)

ABSTRACT

After an earthquake, a nuclear power plant (NPP) may lose offsite power due to the unsatisfactory seismic performance of various electric power grid components, up to and including the station service transformers in the NPP switchyard. The loss of offsite power (LOOP) seismic fragility is a major contributor to seismic risk for most NPPs. Nearly all NPP seismic probabilistic risk assessments (SPRAs) use a conventional LOOP seismic fragility documented in the technical literature (e.g., Electric Power Research Institute (EPRI) SPRA Implementation Guide or "SPRAIG," EPRI (2013)). The conventional fragility is defined by a peak ground acceleration (PGA) median capacity (A_m) of 0.30g and a high confidence of low probability of failure (HCLPF) capacity of 0.09g. This fragility has been used in many SPRAs, although the technical basis has not been well documented. To close that gap, EPRI recently completed a research project (EPRI 3002015993 (2019)) to review the available offsite power seismic performance data, evaluate alternative seismic fragility characterizations, and provide recommendations for LOOP seismic fragility parameters for SPRAs. Performance data is derived primarily from the eSQUG v2.7 database (EPRI (2017)) and is evaluated using two different techniques: one using PGA as the primary damage-predicting parameter, and the other using earthquake magnitude. Sensitivity studies are performed on actual nuclear SPRA results to assess the influence of varying LOOP fragility parameters. This paper summarizes findings from this research.

BACKGROUND

LOOP at an NPP may result from failures at any grid links and/or nodes, including the local switchyard serving the nuclear plant, as well as other generation facilities, transmission lines, and substations. A detailed "bottom-up" analysis of the LOOP seismic fragility could be conducted, which would include calculating the individual fragilities for each grid link and node serving the NPP. However, such a bottom-up approach would require significant plant-specific effort to define the various subcomponent fragilities (e.g., substation equipment, transmission poles, turbine generators, local switchyard transformers) and to convolve them in a system model to calculate the system fragility. Moreover, since the grid is spatially distributed, there are additional complications associated with expressing component fragilities in terms of a reference ground motion local to the plant site. Similar detailed approaches may be rigorous but would require additional resources and may not be more accurate than the conventional LOOP fragility (provided, e.g., in SPRAIG (EPRI (2013)). An alternative to the bottom-up approach is to use experience data on actual post-earthquake grid performance to characterize the probability of seismic LOOP occurrence (i.e., a "top-down" approach). This paper summarizes the implementation of a top-down approach, which has several important advantages:

- Includes the failure probability contribution from all grid subcomponents.

- Represents the performance of a diverse population of grid systems and components exposed to a broad set of earthquakes (i.e., applicability is not limited to a particular site or grid system).
- Reduces the implementation effort for each plant-specific SPRA.

The approach taken in this research consists of investigating available seismic-induced LOOP experience data, developing alternative fragility functions to fit the data (PGA-based and magnitude-based), and providing recommendations for the use of LOOP fragilities in SPRAs.

EARTHQUAKE EXPERIENCE DATA

Database Sites and Earthquakes

The earthquake experience data used in this study consists of documented performance data of offsite electric power at sites with mechanical and electrical equipment similar to those typically found in NPPs. Sample sites include power plants (e.g., fossil, hydroelectric), substations, large hospitals, and heavy industrial facilities. Each site essentially represents a grid node. The data are primarily obtained from the eSQUG database v2.7 (EPRI, 2017). The compiled database includes 197 sites from 32 worldwide earthquakes spanning from 1971 to 2010 (Table 1), with local onsite PGAs ranging from 0.1g to 1.1g.

Table 1: Sites and Magnitudes[1] of Earthquakes Included in the Experience Database.

Earthquake	Magnitude	Number of Sites
1971 San Fernando	6.6	7
1973 Point Mugu	5.8	1
1975 Ferndale	5.7	1
1979 Imperial Valley	6.6	2
1980 Humboldt County	7.0	1
1983 Coalinga	6.7	9
1984 Morgan Hill	6.2	5
1985 Chile	7.8	10
1985 Mexico	8.1	17
1986 Adak	7.7	1
1986 Chalfant Valley	6.0	1
1986 North Palm Springs	5.9	4
1986 San Salvador	5.4	3
1987 New Zealand	6.3	7
1987 Cerro Prieto Mexico	5.4	1
1987 Superstition Hills	6.2	2
1987 Whittier	5.9	18
1988 Alum Rock California	5.3	1
1989 Loma Prieta	7.1	26
1990 Philippines	7.7	6
1991 Sierra Madre	5.8	2
1991 Costa Rica	7.4	8
1992 Cape Mendocino	7.0	4
1992 Landers/Big Bear	7.6	4
1993 Guam	8.0	11
1994 Northridge	6.7	15
1995 Manzanillo	7.6	1
1999 Chi Chi Taiwan	7.6	10
1999 Turkey	7.4	8
2006 Kiholo Bay Hawaii	6.7	7
2007 Niigataken Chuetsu Japan	6.6	3
2010 Baja California	7.2	1
	Total	197

---

[1] The earthquake magnitudes documented in the database may be referring to different scales (e.g., local, moment, surface) or have been updated over time in other databases (e.g., USGS) as new information are compiled. This study uses the documented magnitudes and does not attempt to incorporate moment magnitude uncertainty into the statistical framework. Earthquake magnitude uncertainty is expected to be small compared to the total uncertainty and therefore inconsequential to the overall conclusions of this study.

Failure, Correlation, and Exclusion Criteria

For purposes of this study, "failure" of offsite power (i.e., LOOP) is defined as any interruption of the power supply from the station service transformer to the nuclear plant. This definition intentionally does not account for the offsite power outage duration (i.e., recovery time) for two reasons:

- Offsite power outage duration is typically not documented in the database.
- At NPPs, a LOOP typically triggers shutdown procedures that are not immediately reversible and require plant-specific protocols before offsite power can be restored to the plant.

Most nuclear SPRAs have modelled seismic LOOP with a single fragility to represent all incoming lines as essentially correlated. In some cases, site-specific justifications and sensitivity studies are provided to support treating multiple lines as independent. This study includes a limited review of the presence of multiple (potentially independent) offsite power lines coming into a database site and does not develop new guidance regarding how multiple lines should be treated in a SPRA. The main reason is that information on multiple offsite power lines is not well documented in the database. The following simplifying considerations are made for database sites with multiple incoming lines:

- If all lines failed, they were treated as one correlated instance of LOOP failure.
- Similarly, if all lines survived, they were treated as one correlated instance of LOOP survival.
- If some lines failed and others survived, they were treated as independent failures and survivals.

A given earthquake may be associated with one or multiple site datasets[2], and a given site may have been investigated following multiple events. The statistical analyses in this study approximate each sample of offsite power performance as statistically independent of all others, so datasets that are strongly correlated to each other are consolidated into a single independent sample. For example, sites that experienced the same earthquake, are located close to each other (e.g., less than a few miles), experienced a similar PGA, and/or their power systems performed similarly (e.g., both experienced LOOP) are treated as fully correlated rather than independent samples. Sites reviewed for multiple earthquakes are judged independent samples because ground motions are random and judged uncorrelated with each other, and because the configuration of the grid and onsite equipment evolves over time.

Most eSQUG records for the sites in Table 1 include a description of the power system performance. In most cases, both the offsite power grid and onsite alternating current system are reviewed. Records that provide no information on the power system performance are excluded from the calculations. Records that have some information on offsite power performance, but the information is inconclusive as to whether offsite power was maintained or lost, are identified as having "ambiguous" offsite power performance. Japanese data are excluded from the capacity calculations in this study because Japanese switchyard equipment is considered to be more rugged than elsewhere in the world.

LOOP Database and Ambiguous Data

The LOOP database is developed following the above exclusion and consolidation guidelines. Table 2 lists a subset of the database reviewed in this study and the "best estimate" power performance disposition resulting from an independent review of two engineers with SPRA experience and familiar with SQUG methods and criteria. The initial 197 entries are reduced to 131 samples after removing consolidated and discarded datasets. Of the 131 records, 90 clearly indicate whether the database site lost or maintained offsite power. The remaining 41 records (31% of the total) include varying degrees of ambiguity on the performance of offsite power. For example, some records do not make a clear distinction between "station

---

[2] An eSQUG "site dataset" is a database record comprising a collection of information that summarizes the performance of a site's equipment and systems during and after an earthquake. The word "record" is used interchangeably on eSQUG and in this paper for "dataset."

power" and "offsite power" performance. Others clearly state that power supply was lost from the outside grid but do not indicate whether the cause was a failure of the grid or the performance of some local components such as a transformer or relay within the plant. Others indicate that power was lost to at least one incoming power line but does not describe the performance of all incoming lines. Table 2 identifies the ambiguous records among the subset of data presented.

Table 2: Loss of Offsite Power Database (Subset of Table A-1 of EPRI 3002015993 (2019)).

No.	Earthquake	Site	PGA (g)	EQ Mag.	Best-estimate Disposition
6	1971 San Fernando	Sylmar Converter Station	0.69	6.6	Failure
9	1975 Ferndale	Humboldt Bay Power Plant	0.31	5.7	Survival
33	1985 Chile	Llolleo Water Pumping Station	0.75	7.8	Failure
41	1985 Mexico	Fertimex Power Plant	0.24	8.1	Failure - Consolidate
54	1986 Adak	Adak Naval Station	0.23	7.7	Survival - Ambiguous
55	1986 Chalfant Valley	Hi-Head Hydroelectric Plant	0.25	6.0	Failure - Ambiguous
125	1991 Sierra Madre	Pasadena Power Plant	0.18	5.8	Survival
129	1991 Costa Rica	Limon Telephone Switching Station	0.80	7.4	Failure
137	1992 Cape Mendocino	Pacific Lumber Mill Cogen. Plant	0.46	7.0	Survival
139	1992 Landers/Big Bear	Mitsubishi Cement Plant	0.25	7.6	Exclude
193	2006 Kiholo Bay Hawaii	Waimea Power Plant and Substation	0.56	6.7	Failure - Consolidate
197	2010 Baja California	El Centro Steam Plant	0.54	7.2	Survival

In addition to ambiguity on the offsite power performance, there are several complicating features of the experience data that could influence how various records should be treated in a statistical analysis:

- Some earthquakes affected several sites, but others affected relatively few; statistics derived from the data may have limited diversity and/or may be biased by earthquakes with more samples.
- Some records include information about foreshocks, main shocks, and aftershocks. The ground motion levels associated with the foreshocks and aftershocks are often not well documented, and it is not obvious which should be coupled with the recorded offsite power performance data.
- Some records are for transmission or distribution stations, which are less analogous to NPPs than other database sites, such as fossil plants. It is not obvious whether such sites' disposition as either LOOP survival or failure should be based on the performance of the incoming lines (because they are analogous to the incoming offsite power lines at NPPs), the outgoing lines (because they are analogous to the lines that would feed NPPs), both, or otherwise.
- There is potentially significant variation in the seismic capacity of grids located in different regions and across time.

Based on the number of datasets with ambiguities coupled with the list of complexities outlined above, it is concluded that calculating a new best estimate fragility strictly based on the available data would be impractical and difficult to support with an adequate technical basis. As such, the calculations developed in this study address the substantial ambiguity in the underlying data and the various technical complexities by exploring the results of two sensitivity studies (one based on PGA and one based on earthquake magnitude).

Sources of Conservatism

The statistical population includes several sources of conservatism that are reviewed as part of the two sensitivity studies, mainly:

- Early SQUG post-earthquake investigations focused on sites with the highest degree of damage, and limited efforts were expended to document survival data. There are certainly more sites that maintained power than what is explicitly documented in the experience database. Statistics derived from the database will therefore be biased toward higher probabilities of failure.
- The SQUG post-earthquake investigations focused on large, destructive earthquakes, and thus the database does not include data associated with local PGAs less than 0.10g. The database could therefore be reasonably augmented with data from lower magnitude events and aftershocks, which would likely provide a multitude of survivals in the low PGA range where the conventional LOOP fragility is sensitive.

PGA-BASED CONSERVATIVE BOUNDING FRAGILITY (Sensitivity Study No. 1)

The LOOP database is first reviewed using a simplified data analysis. The samples are initially segregated based on representative 0.1g-wide PGA bins ranging 0.1g to 0.9g. Figure 1 shows a histogram of the data using the mid-range PGA as the horizontal axis. Figure 1 shows that the LOOP database does not include survivals above 0.55g, the bulk of the data are associated with PGAs between 0.1g and 0.4g, and the database includes more failures in the low-PGA bins than expected, reflecting the biased approach taken in developing the eSQUG database.

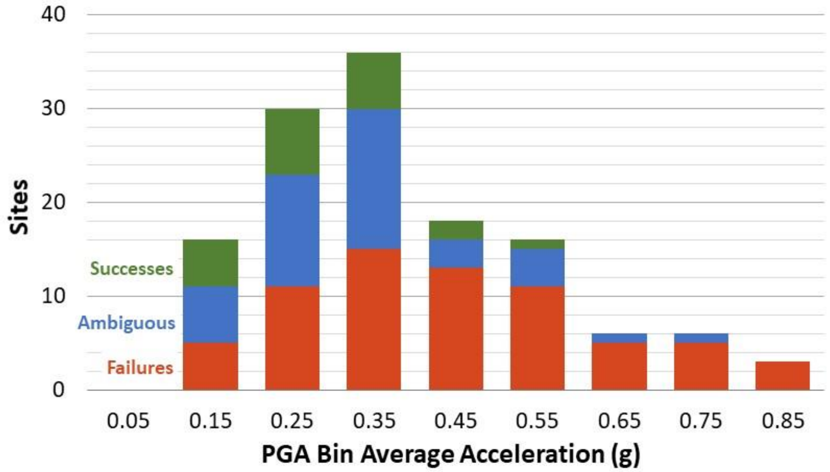

Figure 1. Loss of Offsite Power Performance Histogram.

From the data shown in Figure 1, a range of failure probabilities (P_F) is estimated for each PGA bin as the ratio of failures to total samples under two extreme assumptions: a) all ambiguous performance records conservatively treated as failures; and b) all ambiguous performance records optimistically treated as survivals. The two extreme values of P_F for each PGA bin are displayed in Figure 2 as an uncertainty bar in gray atop the conventional SPRAIG fragility (EPRI (2013)) in blue. Figure 2 indicates that the conventional fragility reasonably fits within the P_F bounds for medium and high PGA bins (i.e., above 0.3g). The fit is less accurate for the 0.15g and 0.25g bins; however, PGA data in this range are known to be conservative based on the SQUG focus on documenting failures at earthquake sites and on larger damaging earthquakes. Therefore, a lognormal, conservative lower bound fragility is proposed (red curve in Figure 2) by scaling the conventional LOOP median capacity (A_m) by one-half while retaining the same variability, such that the P_F exceeds the uncertainty bars in Figure 2 except at 0.15g, where it intercepts the median P_F

computed from the data. This approximation at low PGAs is judged reasonable since the post-earthquake investigations documented in eSQUG focused on damage and failures in larger, destructive earthquakes. The conservative lower bound fragility would be highly likely to envelope the actual P_F for the 0.15g bin if additional data were collected for small and medium earthquakes.

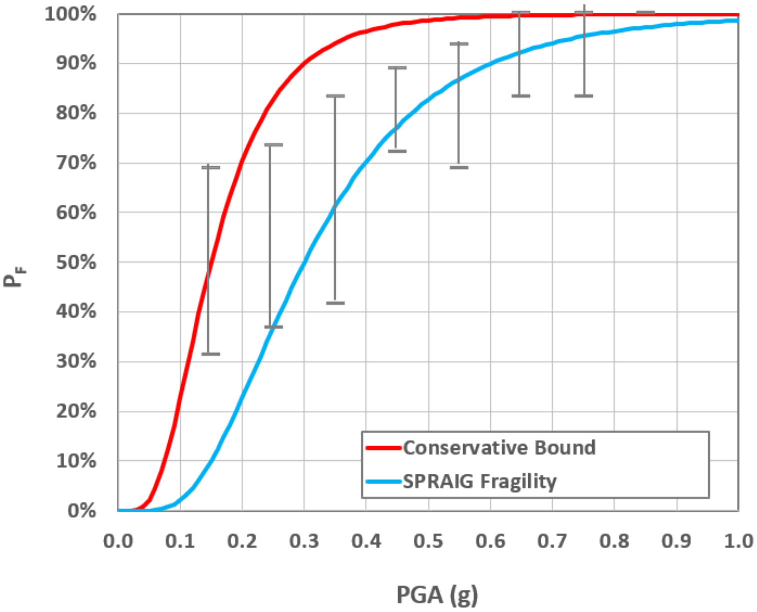

Figure 2. Comparison of Conventional LOOP Fragility to Experience Data Ranges and to Proposed Conservative Bounding Fragility for Sensitivity Study No. 1.

To evaluate the extent to which this bounding fragility might affect SPRA results, several NPP utilities with recent SPRAs were asked to perform sensitivity studies using this bounding LOOP fragility (Sensitivity No. 1). Each participant was asked to report the LOOP fragility that was used in their existing SPRA and the corresponding seismic core damage frequency (SCDF) and seismic large early release frequency (SLERF) estimates along with the updated SCDF and SLERF values using the conservative lower bound fragility proposed here. The sensitivity results for eleven NPP units indicate that SCDF and SLERF increases ranged from 0% to 20% and 0% to 10%, respectively. The average increase from these eleven samples was 10% and 4% for SCDF and SLERF, respectively. The risk increase resulting from using the conservative lower bound fragility is judged non-negligible and could affect the risk insights for some plants. If the risk increase had been negligible, that would have suggested that SPRA risk insights are insensitive to the range of LOOP fragilities that could be reasonably derived from the available data. No further investigation would have been warranted since additional refinement of the LOOP fragility would be inconsequential to SPRA results. However, since the risk increase is non-negligible, Sensitivity No. 1 does not provide an adequate basis to forego further investigation. As such, a further assessment (Sensitivity No. 2) was performed to provide additional insights into the adequacy of the conventional LOOP seismic fragility for SPRAs.

MAGNITUDE-BASED FRAGILITY (Sensitivity Study No. 2)

The eSQUG database includes several earthquakes that affected multiple sites and for which there appears to be a poor correlation between local PGA and LOOP performance. The 2018 Mw 6.6 Hokkaido earthquake provides an anecdotal illustration of why this might happen. The epicenter was roughly 20 km from the Tomatō-Atsuma Coal Plant, which experienced local PGAs of about 0.4g. The local shaking tripped the coal plant and created a grid disturbance that blacked out the entire island. The blackout resulted in a seismic-induced LOOP at the Tomari NPP, which is 100+ km from the epicenter and experienced local shaking on the order of < 0.01g PGA. This event illustrates that seismic-induced grid blackouts can extend across regions much larger than the earthquake's strong motion area. Consequently, seismic-induced LOOP can occur at sites that are far from the epicenter and therefore have relatively small PGAs. As such, local PGA may not be the best predictor of LOOP at a given site.

It is hypothesized that a better seismic LOOP predictor may be a characterization of the earthquake energy throughout the grid rather than the local motion at the NPP. Several potential options were considered for this study, including the earthquake magnitude, the maximum earthquake Modified Mercalli Intensity (MMI), and the earthquake MMI at database sites. Ultimately, the earthquake magnitude was determined to represent the parameter that aligned best with the data collected. Earthquake magnitude represents the total energy released by a fault rupture. Compared to local site PGA, magnitude should therefore be a better representation of the maximum motion experienced by the grid and is expected to be a better predictor of LOOP performance. Additionally, the magnitudes are well known for all the earthquakes in the LOOP database, which eliminates the uncertainty associated with the local site PGA at the database sites. Figure 3 shows the LOOP performance data as a function of earthquake magnitude. The data are segregated into six magnitude bins. As discussed earlier, some of the datasets can be easily dispositioned as either LOOP failure or survival, and others are ambiguous. For each magnitude bin, the failure probability (P_F) is calculated as the ratio of failures to total samples under two extreme assumptions with ambiguous records either 1) conservatively treated as failures or 2) optimistically treated as successes. Figure 3 shows the conservative case in orange and the optimistic case in green. The blue dots at M2.5, M3.5, M4.5, M8.75, and M9.25 represent high-confidence assumed LOOP failure probabilities assigned to the low and high extremes of the magnitude range, at which there are no records in the database. These high-confidence failure probabilities are used in the regression analyses for both the conservative and optimistic cases. The two regression relationships are judged to reasonably bound the range of realistic magnitude-based fragilities.

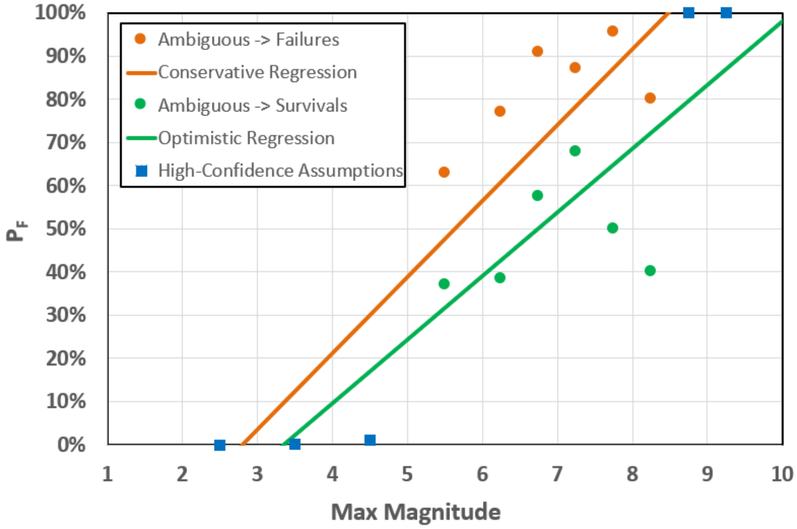

Figure 3. Magnitude-Based Performance Data and Regression Curves.

SPRAs to date have performed risk quantification calculations by expressing the seismic hazard and fragilities in terms of local ground acceleration (e.g., PGA or ground spectral acceleration). To use the magnitude-based fragilities shown in Figure 3 in a conventional SPRA quantification, they need to be converted into a site acceleration-based measure, such as PGA. This conversion can be performed by accounting for the various earthquake magnitudes that are contributing to the site hazard. This is achieved by convolving the magnitude-based fragilities with site-specific seismic hazard deaggregation relationships, which define the contribution of each magnitude-distance pair to the PGA level from each magnitude bin. For this study, sample convolutions are performed using site-specific seismic hazard deaggregation for two sample central and eastern United States (CEUS) NPP sites: one in the northeast and one in the central/southeast United States. The calculation is performed for annual exceedance probabilities (AEPs) from 1E+00 to 1E-05, each of which has a corresponding PGA. Figure 4 shows magnitude deaggregation functions for various return periods (inverse of AEP) for one of the sample CEUS sites.

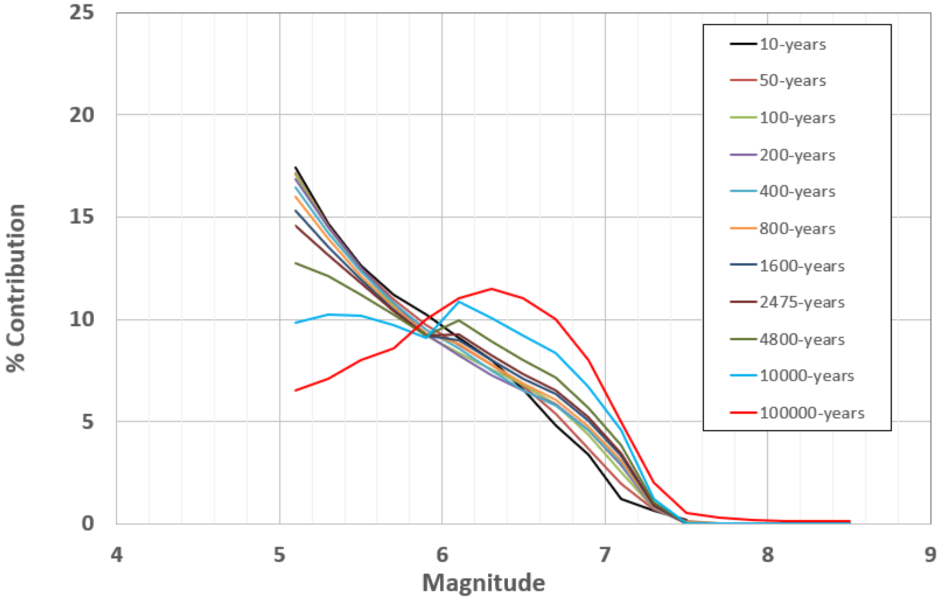

Figure 4. Deaggregation for Various Return Periods for a Sample CEUS Site.

In Figure 5, the P_F vs. PGA relationship (fragility curve) resulting from the convolution is plotted for each sample site and for each of the two bounding magnitude-based fragilities in Figure 3. The site-specific fragilities in Figure 5 are predicated on the assumption that the best predictor of LOOP is the shaking energy (magnitude) experienced by the overall grid, as opposed to local PGA. However, because offsite power performance at an NPP depends not only on the overall performance of the grid but also on the performance of the local switchyard, local accelerations, particularly in the high PGA range, would also be highly likely to cause LOOP. Therefore, Sensitivity Study No. 2 is defined using a step-function fragility (black line in Figure 5):

- For low and medium PGAs, the P_F is estimated as 50%, which lies roughly in the middle of the bounding cases from Figure 5. In this PGA range, this fragility reasonably represents the behavior of the grid assuming LOOP is caused by the shaking level affecting the overall grid.
- Above 0.55g, the P_F is assumed to be 100%. A PGA of 0.55g is selected because there are no documented instances of LOOP survival above the 0.55g bin (Figure 1). The step up to 100% P_F is intended to account for the fact that large local PGAs are highly likely to cause substantial damage to the local switchyard and equipment that would interrupt an NPP's offsite power supply.

Note that, as hypothesized above, the site-specific LOOP P_F vs. PGA relationship is fairly flat for both sites and both bounding magnitude-based fragilities (orange and green curves in Figure 5). This is a consequence of the relatively small variation in magnitudes that dominate the hazard across the domain of PGAs considered. Figure 4 shows that, for return periods ranging from 10 yr to 100,000 yr, the dominant magnitude only varies from about M5 to M6.5. Within this magnitude range, P_F in Figure 3 only ranges from about 40% to 65% for the conservative regression and 25% to 45% for the optimistic regression; hence, the convolved P_F does not vary much with PGA (about 40% to 60% for the two sample sites, Figure 5). However, seismic hazard deaggregation is typically only performed for magnitudes above M5 (Figure 4). Consequently, the deaggregation excludes any contribution from smaller earthquakes, which would be expected to dominate the shortest return periods where the PGA and P_F are low. It is expected that, if events smaller than M5 were included in the hazard and deaggregation, the low PGAs in Figure 5 would be dominated by smaller magnitude events, and would therefore be associated with lower P_F. The proposed step function for Sensitivity No. 2 (black line in Figure 5) is therefore expected to be somewhat conservative in the low-PGA range where it is defined as 50% P_F to approximate the range of fragilities computed for the two sample sites.

Compared to the two CEUS sites examined in this study, the magnitude-based fragilities for other samples sites could have slightly different P_F vs. PGA slopes and failure probabilities. For example, according to Figure 3, if a site's hazard was dominated by M7 earthquakes across the range of relevant return periods, the P_F could range from about 50% to 75%. The magnitude-based fragility proposed here for Sensitivity No. 2 is reasonably consistent even with such an extreme case (i.e., the proposed flat 50% P_F would still fall within the resulting convolved range), and any such site-specific deviations are considered unlikely to substantively affect the principal conclusions of this study.

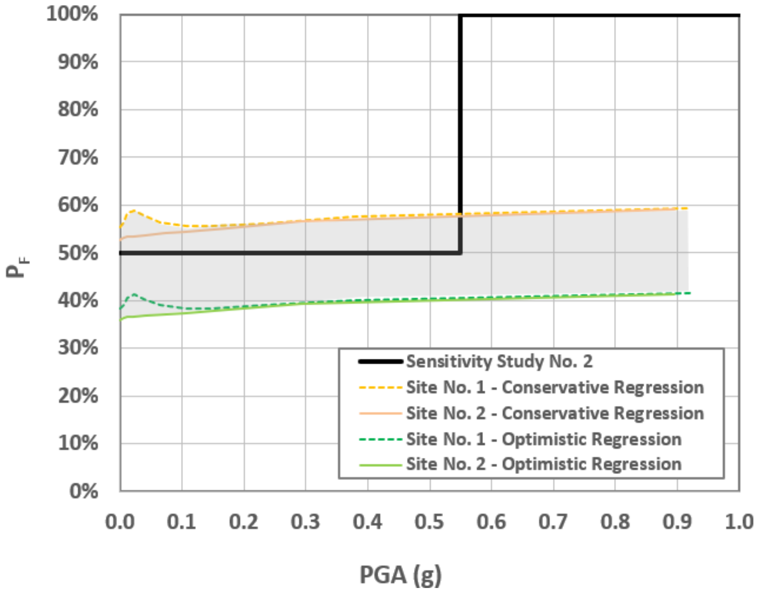

Figure 5. Magnitude-Based Non-Lognormal LOOP Fragility for Sensitivity Study No. 2.

Seven utilities completed Sensitivity Study No. 2 using the proposed step function fragility. Each participant re-quantified their SPRA using the magnitude-based LOOP fragility proposed here and reported the corresponding SCDF and SLERF. The sensitivity results indicate that:

- This step function most often results in a decrease in SCDF and negligible effects on SLERF.
- SCDF and SLERF variations range from -8% to +2% and -2% to +4%, respectively.
- The average variation is -4% and +1% for SCDF and SLERF, respectively.

These results suggest the magnitude-based LOOP fragility formulation produces reasonably similar risk estimates to the conventional LOOP fragility.

CONCLUSIONS

Research Summary

Offsite power at an NPP can be lost for multiple reasons (e.g., switchyard damage, substation damage, grid imbalance, relay tripping, transmission line failure, human error), and the failure location may be far from the NPP site. The eSQUG database (EPRI, 2017) has 131 independent samples of offsite power performance data, which were reviewed for this project; however, the LOOP data is often not well-documented, and a significant portion of that data is ambiguous. The LOOP seismic experience database is segregated into survivals, failures, and ambiguous performance data (Table 2). Analyses of the LOOP data using a PGA reference parameter demonstrate that offsite power system performance is not highly correlated to the local site ground acceleration, particularly for low PGAs (Figure 1). LOOP can be caused by failures throughout the grid serving the NPP; therefore, strong ground motions remote from the NPP can lead to grid failures even if the PGA at the NPP is low. Conversely, at high local PGA levels, the performance of offsite power equipment located at/near the NPP (e.g., the nuclear plant switchyard) may dominate the LOOP seismic failure (Figures 1 and 5). Two sensitivity studies assess the impacts of the ambiguous data and the lack of correlation to the site PGA:

- Sensitivity Study No. 1 – PGA-based, conservative lower bound fragility
- Sensitivity Study No. 2 – Earthquake magnitude-based characterization of the fragility

Key Insights and Recommendations

Sensitivity Study No. 1 asked utilities to evaluate changes in SCDF and SLERF using a conservative lognormal LOOP fragility characterization (Figure 2). Those responses indicate non-negligible SCDF and SLERF increases, suggesting (1) nuclear plant risk is sensitive to reductions in the LOOP fragility, and therefore, (2) the selected bounding case does not provide an adequate basis to forego further investigation of the conventional LOOP fragility. A qualitative assessment of the conventional LOOP fragility in Figure 2 shows that it is reasonably within the bounds of the earthquake experience data at higher PGA values but is outside of the data bounds in the lower PGA values. The experience data in these lower bounds are judged to be conservative, and if these conservatisms were to be removed, the existing LOOP fragility may be within those bounds also.

Sensitivity Study No. 2 asked utilities to evaluate SCDF and SLERF changes using a non-lognormal fragility (Figure 5). This second sensitivity study incorporate a fragility based on earthquake magnitude, which is hypothesized as a more realistic parameter to characterize the LOOP seismic fragility. The results from this second sensitivity study suggest the conventional LOOP fragility produces SCDF and SLERF risks similar to this alternative non-lognormal fragility characterization.

The overall conclusion from this research is that the conventional LOOP fragility fits reasonably well with the available data and is an acceptable best estimate characterization of LOOP fragility. The assessment of offsite power earthquake experience data shows that the conventional LOOP fragility is neither biased nor inaccurate. The following observations and recommendations are provided for LOOP fragility characterization in nuclear plant SPRAs:

- The conventional LOOP seismic fragility values documented in the SPRAIG (EPRI, 2013) are an acceptable best estimate fragility for use in SPRAs.
- LOOP fragility sensitivity studies such as those reviewed in this study can be used in SPRAs to evaluate uncertainty in the LOOP fragility characterization.
- Plants can always choose to perform their own site-specific LOOP fragility characterization; however, it would be difficult to achieve a more appropriate fragility characterization without significant new seismic-induced grid failure performance data.

REFERENCES

EPRI (2013). *Seismic PRA Implementation Guide (SPRAIG)*. EPRI Report 3002000709. Palo Alto, CA.
EPRI (2017). *Seismic Experience Database*, Version 2.7 (eSQUG v2.7). Palo Alto, CA.
EPRI (2019). *Loss of Offsite Power Seismic Fragility Guidance*. EPRI 3002015993. Palo Alto, CA.