Perspective on the Seismic Capacity of Operating Plants

The fleet of operating nuclear power plants was designed using conservative practices, such that the plants have significant margin to safely withstand large earthquake ground motions. This has been borne out for those plants that have actually experienced significant earthquakes in Japan and the United States in recent years.

Ruggedness Resulting from Design Practices

Operating nuclear power plants were designed based on a "deterministic" or "scenario-earthquake" basis that accounted for the largest earthquakes expected in the regional and local areas around the plant. Further margins were added to the predicted ground motions to provide enhanced robustness. The resulting ground motions comprise the design-basis earthquake, most commonly referred to as the safe shutdown earthquake (SSE).

The SSE ground motions were used to design the plants with conservative methods, resulting in significant seismic margins within structures, systems and components (SSCs). These conservatisms are reflected in several key aspects of the seismic design process, including:

- Safety factors applied in design calculations
- Damping values used in dynamic analysis of SSCs
- Bounding synthetic time histories for in-structure response spectra calculations
- Broadening criteria for in-structure response spectra
- Response spectra enveloping criteria typically used in SSC analysis and testing applications
- Response spectra based frequency domain analysis rather than explicit time history based time domain analysis
- Bounding requirements in codes and standards
- Use of minimum strength requirements of structural components (concrete and steel)
- Bounding testing requirements, and
- Additional capacity in the primary materials such as steel and reinforced concrete beyond the elastic capacity credited in designs

These design practices combine to result in margins such that the SSCs will continue to fulfill their functions at ground motions well above the SSE. In general, ground motions at levels 1½ to 2 times the SSE are typically expected to produce only a small probability of failure (e.g., about 1%) for safety-related SSCs. A common parameter used to characterize this margin is the acceleration level at which there remains a high confidence of a low probability of failure (HCLPF). These margins are accounted for in performing more realistic characterizations of seismic performance, such as those that comprise seismic probabilistic risk assessments (PRAs) or seismic margins analyses (SMAs).

Ruggedness Demonstrated by Experience

Earthquake experience at industrial facilities and nuclear power plants demonstrates that well designed (engineered) facilities perform well, even in very large earthquakes. The EPRI Seismic Qualification Utilities Group (SQUG) program has investigated the performance of equipment in large earthquakes at industrial facilities around the world for over 20 years. Insights from that experience have been applied in the design and evaluation of nuclear plant equipment.

A SQUG "reference" ground motion response spectrum was developed to represent the ground motion levels from earthquake experience. The SQUG reference ground motion response spectrum illustrates that equipment in the facilities that experienced these earthquakes survived and continued to function at earthquake levels for which there is confidence in the performance of SSCs at nuclear power plants. Figure 1 shows the SQUG reference ground response spectrum[1] compared with representative SSEs from a number of central and eastern United States (CEUS) nuclear plants. This figure shows that the ground motions based on experience bound the SSE spectra for typical nuclear power plants. Therefore, the insights applied from operating experience support the conclusion that well designed facilities perform well at and above the earthquake levels required for nuclear power plants.

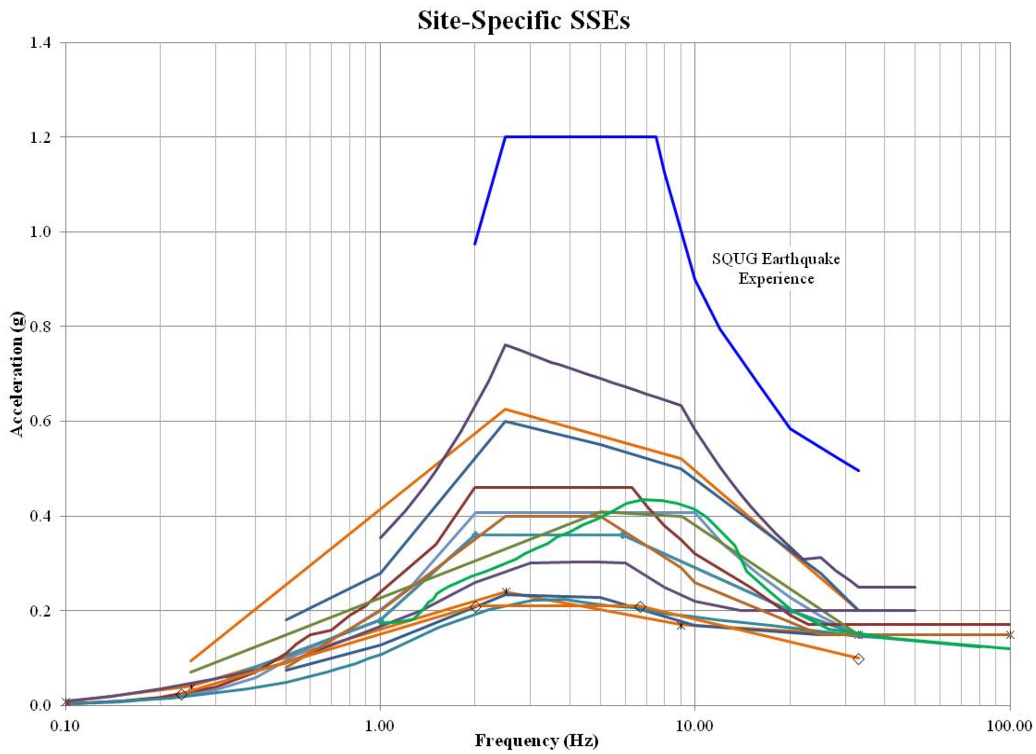

Figure 1. Comparison of Experience-Based (SQUG) Response Spectrum to Representative SSEs

In recent years, several nuclear plants have experienced significant earthquakes. The experience at these plants has further confirmed the seismic ruggedness of the plants at earthquake levels even beyond the initial design basis. This experience is described below for some of these events.

- ***Chūetsu Offshore Earthquake (Japan, 2007).*** In 2007, the Kashiwazaki-Kariwa plant experienced ground motions beyond its seismic design basis from a large earthquake just offshore. While there was some damage to the non-safety, non-seismically designed portions of the plant, none of the safety-related, seismically designed portions of the plant were affected. All safety systems performed as designed to maintain all seven units in a safe condition.

[1] SQUG used 2/3 of the reference ground response spectrum for NPP equipment qualification; however, the full reference spectrum represents the ground motions at the industrial sites.

- ***Great Japan Earthquake (2011)***. In 2011, several nuclear plants on the eastern coast of Japan were affected by one of the largest earthquakes in recorded history. The nuclear plant closest to the source of the earthquake was the Onagawa plant, which safely shut down following the earthquake. Similar to the 2007 experience at Kashiwazaki-Kariwa, there was some damage to the non-safety, non-seismically designed portions of the plant; however, all of the safety-related, seismically designed portions of the plant performed as designed to maintain all three units in a safe condition.

  The Fukushima Dai-ichi and Daini plants are located south of the Onagawa plant and somewhat farther away from the earthquake epicenter. All of the units at both of these plants performed well following the earthquake. It was only when the tsunami generated by the earthquake struck the sites that significant damage occurred. Prior to the time the tsunami reached the respective sites, the units that were operating had tripped, and the safety-related, seismically designed portions of the plants were successfully providing decay heat removal for all of the units. The extensive damage at the Fukushima Dai-ichi plant caused by the tsunami does not diminish the positive evidence of seismic robustness demonstrated by the thirteen affected units.

- ***Mineral, VA Earthquake (2011)***. Later in 2011, the North Anna plant experienced an earthquake originating in Mineral, Virginia. The ground motions at the plant site exceeded a portion of the seismic design basis; however, the safety-related, seismically designed portions of the plant were unaffected and performed as designed to maintain both units in a safe condition. Indeed, there was virtually no observable damage at North Anna, even to non-safety SSCs.

Collectively, the industrial earthquake experience documented by SQUG and the recent earthquake experience at nuclear power plants demonstrate that seismically designed structures, systems, and components are robust, even for ground motions that exceed the seismic design basis.

Significance of High-Frequency Ground Motions

In the CEUS, new ground motion estimates at many sites are expected to include a significant amount of energy content in frequencies above 10 Hz, which for nuclear plants are generally considered to be “high-frequency”.

Limited Potential for High-Frequency Motions to Cause Damage

Nuclear plant SSCs typically have dominant frequency response modes less than 10 Hz. Previous studies have concluded that high-frequency ground motions are not damaging to the majority of nuclear plant SSCs. Examples of these studies include the following EPRI reports:

- Procedure for Evaluating Nuclear Power Plant Relay Seismic Functionality (EPRI NP-7148) [1],
- Industry Approach to Severe Accident Policy Implementation (NP-7498) [2],
- The Effects of High-Frequency Ground Motion on Structures, Components, and Equipment in Nuclear Power Plants (EPRI 1015108) [3], and
- Seismic Screening of Components Sensitive to High-Frequency Vibratory Motions (EPRI 1015109) [4].

EPRI 1015108 summarizes a significant amount of empirical and theoretical evidence, as well as regulatory precedents, that support the conclusion that high-frequency vibratory motions above about 10 Hz are not damaging to the large majority of SSCs in a nuclear power plant. A potential exception is the functional performance of vibration-sensitive components, such as relays and other electrical and instrumentation

devices whose output signals could be affected by high-frequency excitation. EPRI 1015109 provides guidance for identifying and evaluating potentially sensitive components in plant applications that may be subject to high-frequency motions.

Spectral Acceleration versus Spectral Displacements

When subjected to motions at high frequencies at a given spectral acceleration level, an object's displacement is significantly less than the displacement at lower frequencies for the same spectral acceleration level. The very small displacement has little potential to cause damage. Design response spectra are typically illustrated as a plot of acceleration versus frequency, as in Figure 2 (although acceleration is only one parameter used for design of nuclear power plants).

A corresponding plot of displacement versus frequency over the same spectral acceleration range can be constructed, as shown in Figure 3. As this figure shows, there is only very small displacement at frequencies greater than 10 Hz. These small displacements do not cause damage to typical structures, systems, and components in a nuclear power plant. Some electrical components (such as relays, switches, and connectors), although, may be sensitive to high-frequency vibrations. As described below, an extensive program is underway to test components that may be sensitive to high-frequency motions.

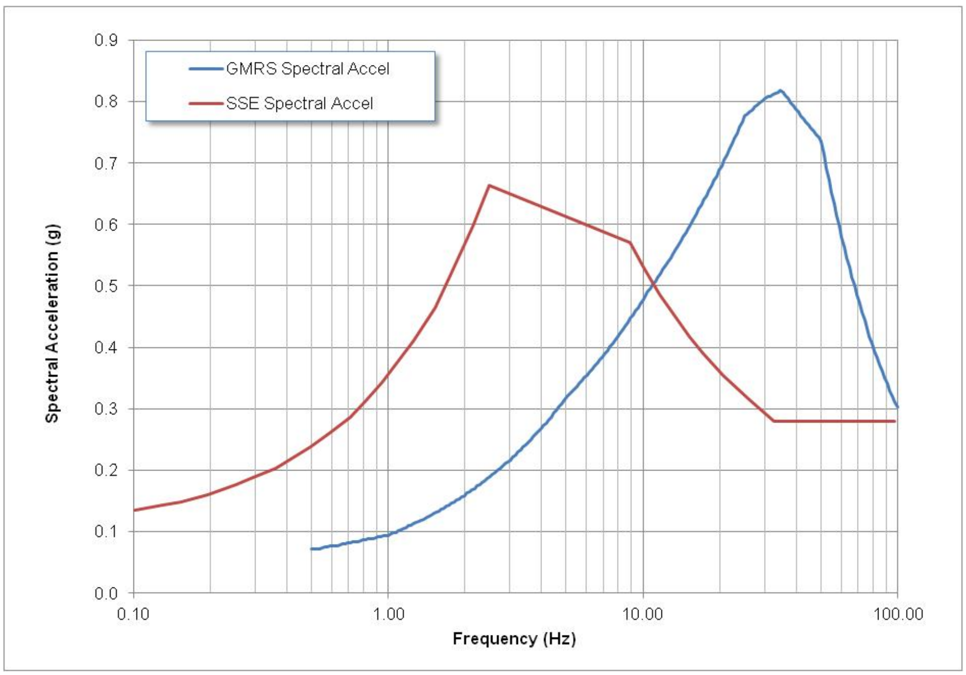

Figure 2. Example Plot of GMRS and SSE, Indicating High-Frequency Exceedances

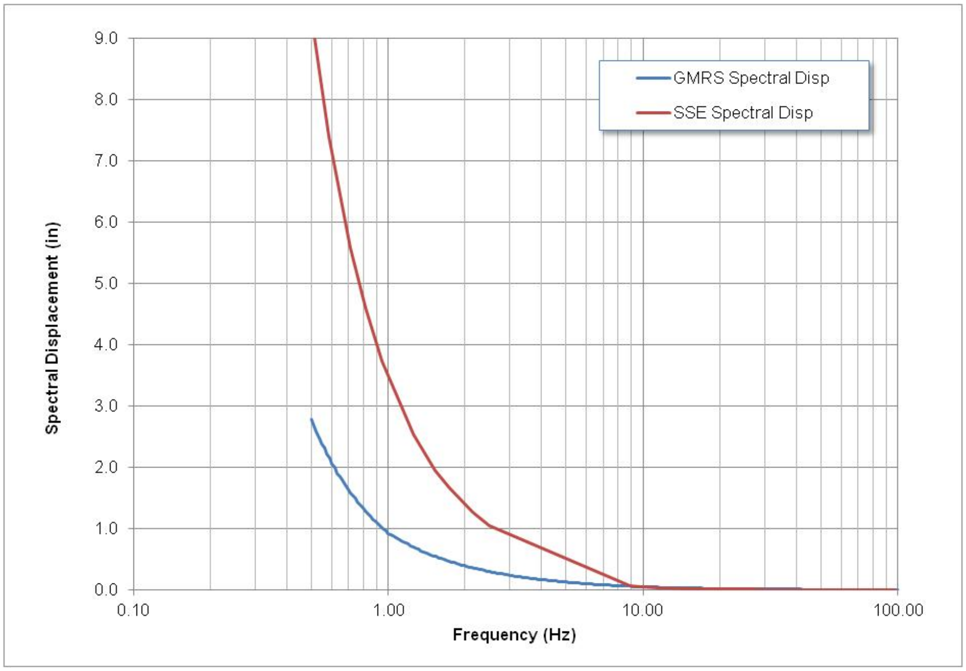

Figure 3. Displacement Corresponding to Ground Accelerations in Figure 2

The NRC has acknowledged the relative inconsequence of high-frequency ground motions. For example, in NUREG-1793 [5], the NRC stated the following:

> "At high frequencies of vibratory excitation, the relative displacement is small and produces insignificant increase in stress. As an example, at 25 Hz and a spectral acceleration of 1.0g, the relative displacement is 0.016 inch. This is too small to cause damage."

Testing Program for Components Potentially Susceptible to High Frequency

EPRI established a test program to develop a more comprehensive understanding of the types of components that could be susceptible to high-frequency motions. As described in EPRI 1025287 [6], Phase 1 of the test program completed in late 2012, developed the appropriate high-frequency testing protocols. Phase 2 testing began in May 2013 using the protocols established in Phase 1, and will continue through March 2014.

As of November 2013, testing had been completed for 100 components. Approximately 75% of those components functioned properly at test levels high enough to bound any practical seismic ground motions. In fact, most of the components performed successfully up to the limits of the shake table (i.e., about 7.5g) as shown in Figure 4. The remaining component high-frequency capacities are above their typical design basis frequency range capacities. The results of the test program will be useful in screening out from further evaluations (i.e., in a SMA or seismic PRA) those components that have especially high capacities, and will help to determine the capacities of those components that cannot be screened out.

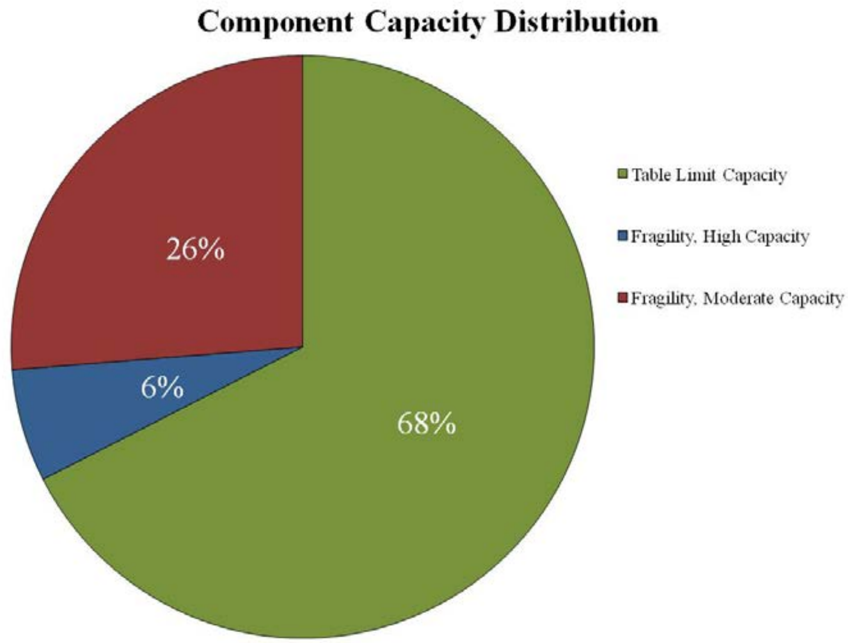

Figure 4. High Frequency Component Capacities: Results of Testing through November 2013

Conclusions Regarding Seismic Ruggedness of Nuclear Power Plants

The SSCs used in nuclear power plants are intentionally designed using conservative methods and criteria to ensure that they have margins well above the required design bases. The ruggedness resulting from these margins has been demonstrated in actual earthquake experiences at nuclear power plants and other industrial facilities. This experience has shown engineered facilities perform well at earthquake ground motions even beyond their design levels.

Several previous studies have concluded that high-frequency ground motions are not damaging to most nuclear plant SSCs. Seismic testing of potentially sensitive components is underway to evaluate potential impacts of high-frequency ground motions. Results to date demonstrate that most components have substantial capacity, and that only a small portion of these potentially sensitive components may require further evaluation.

1 *Procedure for Evaluating Nuclear Power Plant Relay Seismic Functionality*. Electric Power Research Institute Report NP-7148, December 1990.

2 *Industry Approach to Severe Accident Policy Implementation*. Electric Power Research Institute Report NP-7498, November 1991.

3 *Program on Technology Innovation: The Effects of High-Frequency Ground Motion on Structures, Components, and Equipment in Nuclear Power Plant*s. Electric Power Research Institute Report 1015108, June 2007.

4 *Program on Technology Innovation: Seismic Screening of Components Sensitive to High-Frequency Vibratory Motions*. Electric Power Research Institute Report 1015109, October 2007.

5. *Final Safety Evaluation Report Related to Certification of the AP1000 Standard Design*. U.S. Nuclear Regulatory Commission Report NUREG-1793, September 2004.

6 *Seismic Evaluation Guidance: Screening, Prioritization and Implementation Details (SPID) for the Resolution of Fukushima Near-Term Task Force Recommendation 2.1: Seismic*. Electric Power Research Institute Technical Report 1025287, February 2013.