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GUIDELINES FOR NUCLEAR PLANT RESPONSE TO AN EARTHQUAKE

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INTRODUCTION

In the late 1980s, two US nuclear plants nearing initial startup experienced earthquakes that exceeded the plants' interpretations of their Operating Basis Earthquake (OBE); one exceeded the Safe Shutdown Earthquake (SSE). Subsequent inspections and system check-outs revealed no damage to any safety-related (SR) systems, structures and components (SSCs). These results notwithstanding, the plant owners, in consultation with the US Nuclear Regulatory Commission (NRC) staff, spent several months performing additional inspections and re-analyzing the plants' SR SSCs for the measured seismic ground motions. These additional evaluations revealed no damage or problems that required corrective actions.

Based on these experiences and lessons learned, EPRI undertook a project to develop guidelines for nuclear plant response to an earthquake that were intended to provide a consistent, consensus definition of OBE exceedance and a systematic and graded approach for assessing the earthquake damage to the plant, if any, and reasonable actions based on the observed level of damage to demonstrate the readiness of the plant to resume safe operation. The objective of these guidelines was to provide an agreed on process that would allow plant restart following an earthquake as efficiently and timely as possible. Because it was thought at the time that damaging earthquakes that approached and/or exceeded the plants' SSE design basis were very unlikely, especially in the central and eastern US, the guidelines focused on the more probable (and more straight forward to evaluate) earthquakes less than the SSE. The results of this program were published in EPRI report NP-6695, entitled "Guidelines for Nuclear Plant Response to an Earthquake"(1989). Subsequently, the NRC conditionally accepted the EPRI guidelines in their Regulatory Guides 1.166 (1997) and 1.167 (1997).

In the years following issuance of NP-6695, a significant amount of experience has been gained on the effects of earthquakes on nuclear power plants world-wide, in particular in events affecting plants in high seismic hazard areas such as Japan. International Atomic Energy Agency (IAEA) Safety Report

66, (2011) documented lessons learned from all significant earthquake ground motions affecting nuclear power plants pre-2010. Of interest are three multi-unit nuclear plants in Japan that experienced beyond design basis earthquakes over the past several years and one domestic plant (Dominion Energy's North Anna plant in Virginia) that recorded an earthquake with measured ground motion accelerations that slightly exceeded its design SSE level. A summary of experience for these relatively recent earthquakes is given below. None of these plants had comprehensive earthquake response procedures, or had implemented pre-earthquake preparations for a beyond design basis earthquake.

- Onagawa Plants, Japan, 2005 – Base mat accelerations exceeded SSE ground motion. No damage to safety-related (SR) SSCs. Time to restart – 5 to 7 months for three units. (1997)
- Shika Plant, Japan, 2007 – In-structure response spectra (ISRS) exceeded SSE-based in-structure response spectra (ISRS). No damage to SR SSCs. Time to restart – 1 year. (1997)
- Kashiwazaki-Kariwa Plants, Japan, 2007 – All ground spectra exceeded SSE, ISRS significantly exceeded ISRS for SSE. No damage to SR SSCs. Time to restart – 22 to 40 months for seven units. (1997)
- North Anna Plants, VA, USA, 2011 – Base mat spectra slightly exceeded SSE above and below 10 Hz. No damage to SR SSCs. Time to restart - 2 to 3 months for two units. (Information provided by Dominion Energy)

It is likely that implementation of pre-approved response procedures with defined pre-earthquake preparations and graded action levels could have saved many months of down-time for these plants.

Based on these events and the lessons learned in establishing the effects of the earthquakes on the plants and the actions ultimately undertaken to establish the readiness of the plants to restart, EPRI concluded that a significant update of the EPRI NP-6695 was in order. The purpose of this paper is to describe the main changes and additions to the NP-6695 report. These revisions resulted in a comprehensive re-write that was published as EPRI Technical Update report 102588, "Guidelines for Nuclear Plant Response to an Earthquake", (2012).

DISCUSSION

The experience discussed above makes clear that modern earthquake response procedures need to address the beyond design basis level earthquakes as well as the smaller, more probable ones. Because of the greater threat level of large earthquakes, the scope of SSCs potentially affected had to be increased to cover more equipment types. In addition, because plants may be responding to small (<OBE), large (>SSE) and in between earthquake levels, it was decided the response actions needed to be based not only on assessed damage levels at the plant, but also on the observed earthquake level relative to the plant seismic design levels. To address the latter, a matrix approach to establish a prudent action level similar to the approach presented in the recent IAEA guidelines was adopted. Specifically, the Technical Update includes the following main changes and additions to the earlier NP-6695 guidelines:

- The levels of felt earthquakes that are addressed have been increased to include those earthquakes that exceed the plant's design SSE.

- The criteria presented in NP-6695 for determining if a plant's licensing basis OBE has been exceeded, thereby requiring a plant shutdown in accordance with NRC regulations, have been expanded to include limits on spectral velocities in the very low frequency range.

- The scope of SSCs covered in recommended response actions has been expanded to include reactor plant systems, internals and fuel, and both high-frequency- and low-frequency-sensitive devices and components.
- The felt earthquake's damage potential has been re-defined in prescribed Damage Levels (DLs) that are used in part to prescribe recommended actions to assess plant damage and readiness for restart. The measured earthquake ground and in-plant accelerations are also considered in assigning recommended actions to respond to the earthquake. These action levels are presented in a new matrix form.
- A new and important section has been added to cover necessary pre-earthquake preparations and planning, the lack of which has hampered the progress of restart actions in some instances.
- Guidance has been included for cases where the SSE is exceeded to address the need for reevaluation of the plant's seismic hazard and impact on previously performed Seismic Margin Assessments (SMAs) and/or Seismic Probabilistic Safety Analyses (SPSAs).
- Consideration has been given to guidance developed by the IAEA in their recently published guidelines for earthquake response.

The revised and expanded earthquake response plan presented in the 2012 EPRI Technical Update report is divided into five major activities. These actions are described below.

Pre-earthquake Preparations. These actions include preparation of a plant-specific earthquake response plan, including selection of a broad and representative sample of equipment and structures that is base-line inspected prior to an earthquake, and the installation of seismic instrumentation and software necessary to measure the level of a felt earthquake.

Short-Term Actions. Short-term actions are those needed to determine and control the physical condition of the plant immediately following an earthquake and to assess the severity of the earthquake. These actions include the following. The culmination of these actions is determination of the need to shut down the plant.

- Immediate operator actions to maintain the plant in a safe, stable condition while further assessments are made.
- Operator walkdown inspections to identify any significant damage that has occurred in the plant.
- Evaluation of ground motion records from plant seismic instrumentation to determine if the OBE exceedance criterion has been exceeded.
- Determination of the need to shutdown (or remain shut down if the plant is tripped by the earthquake).
- Pre-shutdown inspections to confirm the plant's readiness for shutdown (e.g., availability of shutdown systems, emergency power, etc.)
- Normal plant shutdown when required and the plant's capability to safely shut down has been verified.

Determination of the Earthquake Damage Level, Earthquake Level and Recommended Action Level. These actions include evaluations by experienced engineers to determine the observed damage level of the earthquake based on a special damage scale and the level of the earthquake relative to the plant's design earthquake levels. The results of these evaluations lead to further post-shutdown actions whose

extent and detail are commensurate with the observed damage and earthquake levels. A matrix of recommended actions based on these levels is given in Table 1 below. The Action Levels indicated in this matrix, numbered 1 through 6, consist of a series of specific actions (e.g., inspections, tests, analyses, etc.) that increase in number and scope with increasing levels of both damage and earthquake size relative to the plant design levels. (The extent of the individual actions recommended at each Action Level precludes including them in this paper).

Post-Shutdown Inspections and Tests. Post-shutdown inspections and tests are those needed to determine the physical condition of the nuclear power plant and its readiness to resume operation after it has been shut down based on the criterion described above. These inspections and tests are designed to provide a graded response commensurate with the type and severity of damage found and the level of the felt earthquake.. The recommended post-shutdown actions consist of the following:

- Focused inspections by experienced engineers of the pre-selected sample of representative SSCs. The equipment and structures included in the focused inspections are selected to sample all types of safety-related equipment and structures found in the nuclear power plant, as well as non-safety-related, non-seismically designed equipment and structures which experience has shown to be of low seismic capacity. The purpose of these inspections is to determine the need for expanded inspections and tests.
- Expanded inspections if damage to the pre-selected sample of safety-related SSCs is found or, if damage to other SSCs important to operation is observed during the walkdowns. These expanded inspections by qualified engineers are undertaken to further define and evaluate potential damage to all safety-related (SR) and non-safety-related (non-SR) SSCs required for operation. This information is used to (1) establish corrective actions and repairs that may be required to return the plant to a state of operational readiness, and (2) identify the need and timing for additional analytical and other engineering evaluations which may be prudent to assure the long-term integrity and reliability of the plant.
- Special tests that may be required to identify any hidden damage and to verify the operability of equipment needed for plant operation.

Long-Term Evaluations. Long-term evaluations are those engineering activities needed to confirm that the long-term reliability of safety-related equipment and structures has not been degraded because of the earthquake. Long-term evaluations are not required if plant shutdown is not warranted or if the SSE Exceedance criterion is not exceeded. For significant earthquakes (i.e., earthquakes that exceed the SSE criterion and cause significant damage to the plant), plant readiness for restart under these guidelines will depend upon successful completion of the long-term evaluations. The recommended long-term evaluations include the following:

- Determination of actual seismic loads imposed by the felt earthquake, including determination of actual in-structure seismic response spectra (ISRS).
- Seismic re-evaluations to determine if original design spectra may have been exceeded, and to assess the potential of the actual seismic loads to cause damage. The seismic re-evaluations make use of original design information, modern analytical techniques, seismic capacity data, and where necessary, special nondestructive examinations and functional tests. In the event that the observed earthquake exceeds the plant's design SSE and damage to SR SSCs is observed, re-assessment of the plant seismic hazard, and verification that the plant is adequate for the increased level are recommended.

In summary, the long-term evaluations consist of engineering assessments of selected plant SSCs (i.e., those that have or are suspected to have experienced damage) using the actual event records to assure their long-term reliability. The engineering assessments may be performed on bounding samples of SSCs, if deemed appropriate.

CONCLUSIONS

The combination of the recommended preparatory, short-term, post-shutdown, and long-term actions provides: 1) a rational, experience-based approach for determining the real damage potential of a felt and recorded earthquake, 2) a systematic methodology for assessing plant readiness for restart based on physical inspections and tests, and 3) realistic criteria for assuring the long-term integrity of the plant. They also minimize the likelihood of prolonged plant shutdowns following non-damaging seismic disturbances and place primary emphasis on the physical and functional condition of the plant as a measure of restart readiness as opposed to relying primarily upon analytical evaluations. The underlying premise of these guidelines is that the best indicator of earthquake-related damage to a plant is the plant itself and, to a lesser extent, the measured accelerations at the plant site.

The guidelines presented in the Technical Update represent a consensus of the judgments of experienced seismic/structural engineers, nuclear plant systems specialists, and senior plant operators.

As of this writing, a number of US nuclear plant operators have indicated they have initiated or plan to initiate implementation of these guidelines in their plants.

REFERENCES

MPR Associates, Inc. (1989), "Guidelines for Nuclear Plant Response to an Earthquake" EPRI Report NP-6695.

US Nuclear Regulatory Commission, Regulatory Guide 1.166 (1997), "Pre-earthquake Planning and Immediate Nuclear Power Plant Operator Post-earthquake Actions".

US Nuclear Regulatory Commission, Regulatory Guide 1.167 (1997), "Restart of a Nuclear Power Plant Shut Down by a Seismic Event".

International Atomic Energy Agency (IAEA) Safety Report Series No.66 (2011), "Earthquake Preparedness and Response for Nuclear Power Plants"

Schmidt, W. (2012), "Guidelines for Nuclear Plant Response to an Earthquake", EPRI Technical Update Report 102588.

Table 1 Action Level Matrix

DAMAGE LEVEL	EL 1: < or = OBE	EARTHQUAKE LEVEL EL 2: >OBE, < SSE	EL 3: > SSE
DL 0: No damage to safety-related (SR) SSCs or non-SR SSCs required for operation. Damage limited to non-SR, non-seismically designed Damage Indicators that have no significant impact on plant operation. Typically found in residences, office buildings, etc.	No action required	Action Level 1	Action Level 1
DL 1: No damage to SR SSCs; no damage to rugged industrial type non-SR SSCs. Damage to non-SR SSCs not important to plant operability	Action Level 1	Action Level 1	Action Level 1
DL 2: No damage to SR SSCs; damage to rugged industrial type non-SR SSCs. Damage to non-SR SSCs important to operability	Action Level 2	Action Level 2	Action Level 5
DL 3: Damage to many non-SR SSCs; Slight/isolated damage to less rugged SR SSCs that does not affect equipment functionality	DLs not compatible w/ this EL	Action Level 3	Action Level 5
DL 4: Damage to SR and non-SR SSCs	DLs not compatible w/ this EL	Action Level 4	Action Level 6