

**ANS**

Nuclear Power Plant Response to an Earthquake

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An American National Standard

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American National Standard Nuclear Power Plant Response to an Earthquake

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Foreword

(This foreword is not a part of American National Standard “Nuclear Power Plant Response to an Earthquake,” ANSI/ANS- 2.23-2016.)

This standard describes actions a utility should take preceding and immediately following an earthquake felt at a nuclear power plant site to determine the need to shut the plant down and, if shutdown is required, actions to determine the power plant’s readiness to restart. The plant operator makes the decision to shut down the nuclear power plant based on U.S. Nuclear Regulatory Commission (NRC) regulations that require shutdown in the event that the plant’s design operating basis earthquake (OBE) is exceeded or damage is found during post-earthquake inspections. In some cases shutdown requirements are part of the plant’s licensing basis (e.g., condition of license, final safety analysis report commitment, or technical specifications). An industry/NRC consensus criterion that defines OBE exceedance is presented in Electric Power Research Institute (EPRI) report NP-6695, “Guidelines for Nuclear Plant Response to an Earthquake” (1990); ANSI/ANS-2.10-2003 (withdrawn), “Criteria for the Handling and Initial Evaluation of Records from Nuclear Power Plant Seismic Instrumentation”; and NRC Regulatory Guide 1.166, “Pre-Earthquake Planning and Immediate Nuclear Power Plant Operator Post-earthquake Actions,” issued in 1997. It should be noted that Sec. 4, “Overview of Nuclear Power Plant Response Actions,” in this standard does not specify any requirements or recommendations. Requirements referred to are those that are mandated by long-standing NRC regulations such as the requirement that nuclear power plants have installed seismic instrumentation and that they shut down any time a felt earthquake exceeds the plant’s OBE. It is only a summary listing of the topics and actions covered in the standard. The sections that specify requirements and recommendations of the standard are Secs. 5 through 9. These sections have been carefully written to implement the use of the American Nuclear Society (ANS) policy to use “shall” and “should” for requirements and recommendations, respectively. Clarifications of this criterion and conditions applicable to its implementation are included in this update of ANSI/ANS-2.23-2002 (R2009).

The standard addresses the required sequences of response to an earthquake. It defines pre-earthquake actions, immediate actions, post-shutdown actions, and long-term actions. The findings at each post-earthquake stage indicate the need for, and the level of, any additional effort. The standard specifies that plant personnel perform initial inspections, gather seismic recordings, and reach decisions on the need for plant shutdown and plant readiness for shutdown. If the plant is shut down, the standard defines procedures for near-term actions by plant operators to determine the earthquake effects, with engineers performing focused inspections and tests to determine if structures have sustained significant damage or if operating systems are in any way impaired. The standard then defines actions necessary to establish the readiness of the plant to restart. Finally, the standard provides for long-term, confirmatory evaluations that, in most cases, can be performed after plant restart.

Specifically, the standard specifies actions in five main areas:

- (1) pre-earthquake preparatory actions;
- (2) post-earthquake short-term actions;
- (3) determination of the earthquake damage level, earthquake level, and recommended action level;
- (4) post-shutdown inspections and tests;
- (5) long-term evaluations.

In the years following the issuance of ANSI/ANS-2.23-2002 (R2009), a significant amount of experience has been gained on the effects of earthquakes on nuclear power

plants worldwide, in particular, during events affecting plants in high-seismic-hazard areas such as Japan. International Atomic Energy Agency (IAEA) Safety Reports Series No. 66, “Earthquake Preparedness and Response for Nuclear Power Plants” (2011), documented lessons learned from all significant earthquake ground motions affecting nuclear power plants pre-2010. Of interest are three multiunit nuclear power 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 exceeded its design safe shutdown earthquake level. None of these plants had comprehensive earthquake response procedures; none had implemented pre-earthquake preparations for a beyond-design-basis earthquake; and none had visible damage to safety-related structures, systems, or components. Nevertheless, many months (in some cases more than a year) and thousands of man-hours of plant inspections and evaluations were spent justifying restart of the plants. A comprehensive earthquake response plan such as the one described herein could have significantly focused and reduced these efforts.

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, a significant update of EPRI report NP-6695 [the technical basis for ANSI/ANS-2.23-2002 (R2009)] was prepared and published in 2013 as EPRI report 3002000720, “Guidelines for Nuclear Plant Response to an Earthquake.” This revised ANSI/ANS-2.23 standard incorporates the significant changes and additions included in EPRI report 3002000720, which serves as the commentary for this standard. It is also consistent with IAEA Safety Reports Series No. 66. Applicability of the aforementioned documents is specifically limited to nuclear power reactor-type plants.

This standard might reference documents and other standards that have been superseded or withdrawn at the time the standard is applied. A statement has been included in the references section that provides guidance on the use of references.

This standard does not incorporate the concepts of generating risk-informed insights, performance-based requirements, or a graded approach to quality assurance. The user is advised that one or more of these techniques could enhance the application of this standard.

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Nuclear Power Plant Response to an Earthquake

1 Scope

This standard¹⁾ is a major update of ANSI/ANS-2.23-2002 (R2009) [1]²⁾. It describes actions that the owner of a nuclear power plant shall take to prepare for and respond to a felt earthquake at the plant(s), including the need for plant shutdown; actions to determine the readiness of the plant to resume operation; and those evaluations necessary to verify the long-term integrity of safety-related (SR) and important structures, systems, and components (SSCs). It also includes a consensus definition of operating basis earthquake (OBE) exceedance, beyond which U.S. regulations require plant shutdown. Application of this revised standard provides a comprehensive, balanced plan for the response of a nuclear power plant to an earthquake.

This standard does not cover those operator actions that are performed in connection with safe operation and control of the nuclear power plant during and following an earthquake. These operations are specified in plant operating procedures, emergency procedures, alarm response procedures, and other conditions of the plant's license. Likewise, it does not cover required reporting and communications with the U.S. Nuclear Regulatory Commission (NRC). It is not applicable to nuclear facilities other than licensed nuclear power plants.

2 Purpose

The purpose of this standard is to specify actions that shall be included in plant-specific procedures that describe actions to be taken in preparation for and response to a felt earthquake at the plant. The objectives of these procedures are to determine the following:

- the effects of the earthquake on the physical condition of the nuclear power plant;
- whether shutdown of the plant is required, based on observed damage to the plant or because the OBE has been exceeded;
- the readiness of the plant to shut down if shutdown is required due to an earthquake;
- the readiness of the plant to resume operation from a shutdown condition based on physical inspections and tests and the successful completion of operability tests and analytical evaluations, where required, that demonstrate that the limiting conditions for operation as defined in the plant technical specifications are met.

The combination of the preparatory, short-term, post-shutdown, and long-term actions provides a rational, experience-based approach for determining the real damage potential of a felt and recorded earthquake, a systematic methodology for assessing plant readiness for restart based on physical inspections and tests and on realistic criteria for assuring the long-term integrity of the power plant. These actions also minimize the likelihood of prolonged plant shutdowns following nondamaging seismic disturbances and place primary emphasis on the physical and functional conditions of the plant as a measure of restart readiness, as opposed to relying primarily upon analytical evaluations and instrumental data alone.

¹⁾ The current standard, ANSI/ANS-2.23-2016, is herein referred to as "this standard."

²⁾ Numbers in brackets refer to corresponding reference numbers in Sec. 10, "References."

3 Acronyms and definitions

For the purpose of this standard, the following acronyms, words, and phrases are defined.

3.1 Acronyms

AC: alternating-current
AL: action level
ASME: American Society of Mechanical Engineers
BPVC: *ASME Boiler and Pressure Vessel Code*
BWR: boiling water reactor
CAP: corrective action program
CAV: cumulative absolute velocity
DC: direct-current
DL: damage level
EL: earthquake level
EPRI: Electric Power Research Institute
GERS: generic equipment ruggedness spectra
HF-sensitive: high-frequency-sensitive
IAEA: International Atomic Energy Agency
IGSC: intergranular stress corrosion
ISRS: in-structure response spectra
LBB: leak before break
non-SR: non-safety-related
NRC: U.S. Nuclear Regulatory Commission
OBE: operating basis earthquake
PSA: probabilistic safety assessment
PWR: pressurized water reactor
RCS: reactor coolant system
SMA: seismic margin assessment
SPSA: seismic probabilistic safety assessment
SR: safety-related
SSCs: structures, systems, and components
SSE: safe shutdown earthquake
TRS: test response spectrum

3.2 Shall, should, and may

The word “shall” is used herein to denote a requirement; the word “should” is used to denote a recommendation; and the word “may” is used to denote permission, neither a requirement nor a recommendation.

3.3 Definitions

cumulative absolute velocity (CAV) and standardized CAV: The time integral of absolute acceleration over the duration of the strong shaking. The “standardized CAV” algorithm in EPRI report TR-100082-T2 [2] ignores small-amplitude shaking and is therefore more stable. This quantity has been shown to be a good indicator of the damage potential of an earthquake ground motion. In this standard, CAV means standardized CAV. Appendix A gives background and detailed information on the definition of the standardized CAV.

felt earthquake: An earthquake of sufficient size such that (a) the vibratory ground motion is felt at the nuclear plant site and recognized as an earthquake based on a consensus of the control room operators on duty at the time and (b) for plants with operable seismic instrumentation, the seismic triggers installed at the plant are activated.

functional damage: Significant damage to plant SSCs, either physical or other, that impairs the operability or reliability of the damaged item to perform its intended function. Minor damage such as slight or hairline cracking of concrete elements in structures does not constitute functional damage.

limiting conditions for operation: Those conditions that must be satisfied during specific modes of operation of the nuclear power plant. Limiting conditions for operation are defined in 10 CFR 50.36(c)(2) [3] as the “lowest functional capability or performance levels of equipment required for safe operation of the facility.” They are listed individually in the plant technical specifications and provide the basis for operation of the plant within the conditions of the operating license.

malfunction: Inability of a structure, system, or component to perform its required function. Malfunction may be due to physical damage or to the temporary loading caused by the earthquake, for example, shaking causing “chatter” of electrical devices.

non-safety-related (non-SR): As in non-safety-related SSCs.

operable: A system, subsystem, train, component, or device is considered operable when it is capable of performing its specified function(s) in accordance with plant technical specifications. Implicit in this definition is the assumption that all necessary instrumentation, controls, normal and emergency electrical power sources, cooling or seal water, lubrication, or other auxiliary equipment that are required for the system, subsystem, train, component, or device to perform its function(s) are also capable of performing their related support function(s).

operating basis earthquake (OBE) exceedance: The OBE is considered to have been exceeded if the damage parameters based on the vibratory motion due to an earthquake exceed the limit values specified in Sec. 6.4.

operating basis earthquake (OBE) ground motion: An earthquake ground motion that could reasonably be expected to occur at the plant site during the operating life of the plant considering the regional and local geology, seismology, and specific characteristics of local subsurface material. It is that earthquake ground motion for which those features of the nuclear power plant, necessary for continued operation without undue risk to the health and safety of the public, are designed to remain functional. The OBE level earthquake ground motion is referred to in most international applications as the Seismic Level 1 (SL1) EL.

physical damage: Damage to plant SSCs that can be detected by visual inspections, nondestructive examinations, and/or tests (e.g., broken parts, cracks, plastic deformation, misalignment of joining components, excessive wear, etc.). The damaged item may or may not be capable of performing its intended function.

safe shutdown earthquake (SSE) exceedance: The SSE is considered to have been exceeded if the damage parameters based on the vibratory motion due to an earthquake exceed the limit values specified in Sec. 6.4.

safe shutdown earthquake (SSE) ground motion: Earthquake ground motion for which certain SSCs are designed to remain functional. These SSCs are those necessary to ensure

- the integrity of the reactor coolant pressure boundary;
- the capability to shut down the reactor and maintain it in a safe shutdown condition; or
- the capability to prevent or mitigate the consequences of accidents that could result in potential off-site exposures of nuclear radiation exceeding allowable amounts.

The SSE level earthquake ground motion is referred to in most international applications as the Seismic Level 2 (SL2) EL.

safety-related (SR): As in safety-related SSCs.

significant damage: Significant damage (physical or functional) is considered to be damage that has the potential to adversely affect the functionality or reliability of structures, systems, or components required for the safe operation of the nuclear power plant. Damage may be indicated by visual inspections, nondestructive examinations, and/or tests. Significant damage may be indicated by each or a combination of any or all of the following indicators:

- *concrete structures:* new earthquake-induced cracks in concrete >0.06 in. wide and those that extend through the thickness of the member, spalling of concrete, visible distortion of frames³⁾;
- *steel structures:* new earthquake-induced visible plastic deformation or cracking of joints, visible distortion of bolts, bolt holes, or steel members;
- *pipng:* through-wall cracks in pipe resulting in leakage, evidence of new or increased leakage at joints or connections following an earthquake, complete or partial severance of pipe, significant ($>10\%$) flow reduction due to cross-section impairment or flow control valve function. Plastic deformation of piping or supports identifiable by visual inspection⁴⁾;
- *system supports:* significant damage is identified when a support is no longer capable of performing its support design function.⁵⁾ Examples of supports to be considered are distribution system supports (piping, cable trays, and HVAC ducts), pressure vessel supports (reactor, pressurizer, steam generator, heat exchangers, torus, condensers, etc.), and water storage tank supports;
- *mechanical or electrical equipment:* visible distortion of anchorage system; sliding of the base of anchored components; rupture (leakage) of attached distribution system; general crimping or buckling of the equipment body, shell, or housing restricting the component from performing its function⁶⁾; cracking of battery jars; and loose or broken electrical connections;
- *rotating equipment:* excessive noise, vibration, or temperatures in operating equipment.

surveillance: Surveillance is that process whereby systems and components that are essential to plant nuclear safety during all modes of operation or that are necessary to prevent or mitigate the consequences of accidents are checked, tested, calibrated, and/or inspected as necessary to verify performance and availability.

surveillance tests: Those tests performed at regular intervals to demonstrate the availability and operability of components and systems. Surveillance tests are identified in the plant technical specifications and consist of checks, tests, calibrations, and inspections to verify availability and performance of the tested component or system.

time-history recorder: An instrument capable of sensing and recording acceleration versus time. The resulting recorded time histories may be stored locally and/or transmitted to other storage devices for processing and permanent storage. The components of the time-history recorder (acceleration sensor, recorder, and seismic trigger) may be assembled in a self-contained unit or may be separately located.

³⁾ Concrete cracks ≥ 0.06 in. may be indicative of yielding of reinforcement.

⁴⁾ Damage to insulation and denting or scratching of pipe are not considered significant damage.

⁵⁾ Bent or deformed supports as long as they are capable of performing their design function are not considered significant.

⁶⁾ Scratches and localized denting of the equipment body or housing are not considered significant.

4 Overview of nuclear power plant response actions

The earthquake response plan described herein is divided into five major actions. These actions are detailed in the following sections of the standard and are summarized below⁷⁾:

- (1) *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 baseline inspected prior to an earthquake, as well as the installation of seismic instrumentation and software necessary to measure the level of a felt earthquake. The measured ground motions and related parameters are compared to OBE and safe shutdown earthquake (SSE) exceedance criteria for the plant. (These criteria are described in Sec. 6.4.);
- (2) *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. They include the following:
 - (a) immediate operator actions to maintain the plant in a safe, stable condition while further assessments are made,
 - (b) operator walkdown inspections to identify any significant damage that has occurred in the plant,
 - (c) evaluation of ground and structure motion records from plant seismic instrumentation to determine if the OBE exceedance criterion has been exceeded,
 - (d) determination if plant shutdown is required (or the plant is required to remain shut down if it is tripped by the earthquake),
 - (e) pre-shutdown inspections to confirm the plant's readiness for shutdown (e.g., availability of shutdown systems, emergency power, etc.).

The results of these actions provide a safe response to the earthquake and the bases for the determination if shutdown of the plant is required;

- (3) *Determination of the earthquake damage level (DL), earthquake level (EL), and action level (AL).* These actions include evaluations by experienced engineers and operators to determine the observed DL of the earthquake based on a special damage scale and the level of the earthquake relative to the plant's design OBE and SSE ELs. The results of these evaluations lead to further post-shutdown actions whose extent and detail are commensurate with the observed DLs and ELs. A matrix of required actions based on these levels is given in Table 1. The ALs prescribed in this matrix consist of a series of specific actions (e.g., inspections, tests, analyses, etc.) that increase in number and scope with increasing levels of both observed damage (DL) and earthquake size (EL) relative to the plant design levels;
- (4) *Post-shutdown inspections and tests.* Post-shutdown inspections and tests are those required 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 types of required post-shutdown actions consist of the following:

⁷⁾ This section does not specify any requirements or recommendations. Requirements referred in this section are those that are mandated by long-standing NRC regulations.

- (a) 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 SR equipment and structures found in the nuclear power plant, as well as non-safety-related (non-SR), nonseismically designed equipment and structures that experience has shown to be of low seismic capacity. The selected sample shall include the SSCs that are most vulnerable (e.g., SSCs that are more fragile based on experience and are in locations of highest seismic demand). The purpose of these inspections is to determine if expanded (i.e., supplementary) inspections and tests are required,
 - (b) expanded inspections if damage to the preselected sample of SR SSCs is found or if damage to other SSCs important to safe plant operation is observed during the walkdowns. These expanded inspections by qualified engineers are required to further define and evaluate potential damage to all SR and non-SR SSCs required for operation. This information is used to (1) establish corrective actions and repairs that are 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 that are required or prudent to assure the long-term integrity and reliability of the plant,
 - (c) special tests that are required to identify any hidden damage and to verify the operability of equipment needed for plant operation;
- (5) *Long-term evaluations.* Long-term evaluations are those engineering activities required to confirm that the long-term reliability of SR 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 and no significant damage is observed. For earthquakes that exceed the SSE criterion and cause significant damage to the plant, plant readiness for restart shall include successful completion of the long-term evaluations. The long-term evaluations shall also be performed for conditions where significant damage is observed due to an earthquake less than or equal to the SSE. The long-term evaluations include the following:
- (a) calculation of seismic loads imposed by the felt earthquake and corresponding in-structure response spectra (ISRS),
 - (b) seismic reevaluations to determine if original design spectra have been exceeded and to assess the potential of the induced seismic loads to cause damage. The seismic reevaluations should 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, reassessment of the plant seismic hazard and verification that the plant is adequate for the increased level shall be performed.

In summary, the long-term evaluations consist of engineering assessments of selected plant SSCs that have or are suspected to have experienced damage considering the recorded earthquake motions, to assure their long-term reliability. The engineering assessments may be performed on bounding samples of SSCs, if deemed appropriate.

5 Pre-earthquake preparations and planning

Since publication of ANSI/ANS-2.23-2002 (R2009) [1], there have been a number of significant earthquakes at nuclear power plants at which design ELs have been exceeded, and yet no significant damage has occurred to SR SSCs. Despite these observations, most of these plants have spent many months performing extensive analyses and tests to confirm the structural integrity and functionality of

important SSCs prior to restart. In each of these cases, the existence and implementation of a clear and thorough earthquake response procedure in advance could have eliminated a significant amount of unnecessary time and effort. As a consequence, pre-earthquake preparations, including development and implementation of such a response procedure, are key elements in an efficient, cost-effective earthquake response plan.

The essential pre-earthquake preparations and related requirements are described below.

5.1 Responsibilities

Responsibilities of utility management, plant management and operations personnel, and engineering representatives shall be defined.

5.2 Definition of plant shutdown criteria

Since 1973, NRC regulations for nuclear power plants require that plants shut down (or remain shut down) if a felt earthquake exceeds the plant's OBE, although the specific ground motion and other response parameters that define the OBE (and therefore exceedance of the OBE) may not be specified. These would normally be defined in plant-specific licensing documents, but for some U.S. plants, depending on their vintage, this may not be the case. In response to this situation, the U.S. nuclear industry, with consultation and input from the NRC, developed a standardized OBE exceedance criterion [4, 5] that has been conditionally accepted by the NRC in Regulatory Guide 1.166 [6] and is considered acceptable for all U.S. licensed nuclear power plants. This "consensus" OBE exceedance criterion (and also the SSE exceedance criterion used herein to define response actions) includes a response spectrum check and the calculation and evaluation of the parameter cumulative absolute velocity (CAV), defined in Sec. 3. The OBE and SSE exceedance criteria are described in detail in Sec. 6.4. They are the criteria that are intended to be used in applying this standard for plant shutdown decisions and for subsequent response actions. However, since all U.S. plants are obligated to comply with their plant-specific licensing commitments, plant licensees that elect to implement this standard should review their plant-specific licensing requirements to determine if clarifications and/or amendments to their license are required to apply the OBE exceedance criteria described herein for the purpose of complying with applicable NRC requirements for plant shutdown following a felt earthquake. For example, it may be necessary for some plants to formally adopt the consensus OBE exceedance criterion described in this standard as part of their licensing documents. Guidance on this subject is provided in Electric Power Research Institute (EPRI) report 1024889 [7] and NRC Final Policy Statement on Technical Specifications for Nuclear Power Reactors [8].

5.3 Seismic instrumentation

U.S. Nuclear Regulatory Commission regulations for nuclear power plants require that suitable instrumentation be provided so that the seismic response of nuclear power plant features important to safety can be evaluated promptly after an earthquake. Seismic instrumentation and data acquisition systems capable of recording and saving acceleration time histories of significant earthquakes are required to fully implement the requirements of this standard. Software to compute seismic response spectra and the damage parameter standardized CAV is also required, as described in Sec. 6.4 and Appendix A. The system shall be capable of computing these parameters within 4 hours of the earthquake. Guidance for new applications of seismic instrumentation and data acquisition systems that reflect the current state of practice is contained in Appendix B and in EPRI report 1024889 [7].

Free-field measurements are required for determining the CAV, unless otherwise justified. Free-field measurements are also intended for calculating the observed earthquake's seismic response spectra to be compared to plant design OBE and SSE seismic response spectra. However, if a plant's design OBE and