Topical Report : Preclosure Seismic Design Methodology for a Geologic Repository at Yucca Mountain

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Yucca Mountain Site Characterization Project

TOPICAL REPORT YMP/TR-003-NP

PRECLOSURE SEISMIC DESIGN METHODOLOGY FOR A GEOLOGIC REPOSITORY AT YUCCA MOUNTAIN

Revision 2

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U.S. Department of Energy
Office of Civilian Radioactive Waste Management
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1.2 CONTENT OF THE SEISMIC TOPICAL REPORTS

This topical report is the second in a series of three reports that the DOE has planned that together will describe the preclosure seismic design process. The relationship of the three topical reports is illustrated in Figure 1-1. Topical Report I, *Methodology to Assess Fault Displacement and Vibratory Ground Motion Hazards at Yucca Mountain* (DOE 1994a), describes the DOE methodology for assessing vibratory ground motion and fault displacement hazards. Topical Report II (this report) describes the DOE preclosure seismic design methodology and design acceptance criteria and establishes seismic hazard levels that are appropriate for design. The DOE anticipates that a third report, currently scheduled for fiscal year 1998, will describe the results of the assessment of the vibratory ground motion and fault displacement hazards at Yucca Mountain and the determination of the appropriate design bases for these hazards.

The content of the three seismic reports is described in more detail in the following paragraphs.

Topical Report I--Topical Report I describes the DOE methodology for probabilistic assessment of vibratory ground motion and fault displacement hazards. The methodology involves a series of workshops structured so that multiple experts can interact to evaluate hypotheses and models using the Yucca Mountain site and area geological, geophysical, and seismological data sets. The data sets will be made available to all participant experts uniformly. Importantly, the methodology requires that the experts specifically evaluate all hypotheses and models that have credible support in the data. The product of the methodology is multiple interpretations by the experts of seismic sources, source properties, and evaluations of ground motion, all of which include specific expressions of uncertainty. The methodology does not involve expert opinion, which implies judgments unconstrained by data or normal scientific rigor, but instead employs normal earth science procedures and practice, and carries the usual past practice one step further by requiring uncertainty in the interpretations to be specifically expressed. Moreover, it forces a consistent level of scientific rigor, a comprehensive and consistent consideration of data, and documentation of all interpretations.

Additional information on the methodology is contained in *Probabilistic Analyses of Ground Motion and Fault Displacement at Yucca Mountain*, Yucca Mountain Study Plan 8.3.1.17.3.6 (DOE 1995a).

Topical Report I does not provide the values of vibratory ground motion and fault displacement hazards for design of the facility SSCs; it describes only the methodology for hazard assessment. The application of this methodology at the Yucca Mountain site will yield hazard estimates that will, together with planned deterministic evaluations, comprise the information base considered in determining preclosure design basis vibratory ground motion and fault displacement values. The hazard estimates will also be used in the assessment of postclosure waste containment and isolation performance.

Topical Report II--Topical Report II (this report) describes the design methodology and criteria that the DOE intends to implement to provide reasonable assurance that vibratory ground motions and fault displacements will not compromise the preclosure safety functions of SSCs important to safety. The seismic design methodology and criteria implement the requirements of 10 CFR 60, including the requirement in the recent ruling (61 FR 64257) to identify Category-1 and -2 design basis events. This report establishes hazard probability levels that are appropriate for determining the two levels of design basis vibratory ground motions and the two levels of design basis fault displacements. Acceptance criteria for both surface and underground facilities are provided for vibratory ground motion and fault displacement design. In addition, the report provides criteria for fault avoidance, which is the DOE preferred approach to mitigating fault displacement hazards. Seismic design considerations for waste packages, which will function on the surface and underground and which have a number of unique performance requirements, are discussed. NRC guidance documents for the seismic design of nuclear power reactors that can appropriately be applied to preclosure seismic design of the repository are identified.

Topical Report III--A third seismic topical report is planned for completion in fiscal year 1998. The DOE intends to conduct and document the probabilistic seismic hazard assessment during fiscal year 1997 using the methodology of Topical Report I. Using the results of the hazard assessment, preclosure seismic design inputs will be developed and documented in a Seismic Design Report, which is scheduled for the second quarter of fiscal year 1998. The third topical report would document the results of both of these efforts for formal NRC staff review.

It is expected that seismic design inputs will be determined from controlling earthquakes identified from a disaggregation of the probabilistic seismic hazard results and from a consideration of deterministic hazard assessments. Disaggregation of the hazard results will be carried out for hazard exceedance probability levels established in Topical Report II and for ground motion frequencies of interest. Different earthquakes may control the hazard in different frequency ranges. Ground motions from the controlling earthquakes will be evaluated deterministically.

In addition to conducting the probabilistic hazard assessment. the DOE intends to perform deterministic evaluations of Type I faults and candidate Type I faults that lie within 5 km of the Yucca Mountain site, including estimations of maximum earthquake magnitudes for the faults. The DOE intends to evaluate where the hazards from these deterministic evaluations fall within the probabilistic results. This comparison will provide a check on the reasonableness of the vibratory ground motion and fault displacement design bases.

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3.0 DESIGN OF STRUCTURES, SYSTEMS, AND COMPONENTS FOR VIBRATORY GROUND MOTION

This section presents and rationalizes the reference exceedance probabilities that the DOE plans to use in identifying Frequency-Category-1 and -2 design basis vibratory ground motions. It then discusses the design acceptance criteria that the DOE plans to apply in the preclosure seismic design of structures, systems and components (SSCs) that are important to safety. Design acceptance criteria are discussed specifically for SSCs on the ground surface, for underground openings, and for other underground SSCs.

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3.1 HAZARD LEVELS FOR DESIGN BASIS GROUND MOTIONS

In accordance with the recent 10 CFR 60 rulemaking discussed in Section 2.1.1, the DOE will identify SSCs that are important to (radiological) safety. The DOE procedure for identifying these SSCs is summarized in Appendix B. The classification process involves the identification of Frequency-Category-1 and Frequency-Category-2 design basis events and event-initiated accident scenarios and the calculation of corresponding exposures to workers and the public. The calculated exposures are compared to regulatory limits, and any SSC that must continue to function after a design basis event to ensure the exposure limits are not exceeded is classified as important to safety. No SSCs have yet been classified. Note that SSCs may be important to safety for both Frequency-Category-1 and Frequency-Category-2 design basis events. Where this occurs, the most stringent (i.e., Frequency-Category-2) design basis will apply.

The regulatory definitions of Category-1 and -2 design basis events are qualitative descriptions of the likelihood of occurrence before permanent closure of the geologic repository operations area. For use in SSC classification, which requires knowledge of the design basis events and calculation of radiation exposures, these definitions require quantitative interpretations. As discussed next, the DOE intends to use mean annual exceedance probabilities of 1.0E-03 and 1.0E-04, respectively, as reference values in determining the Frequency-Category-1 and -2 design basis vibratory ground motions. These reference values will be used in the disaggregation of probabilistic seismic hazard estimates to identify those earthquakes that control the seismic hazard at the reference probabilities. The identification of controlling earthquakes and the DOE determination of the design basis ground motions are planned to be detailed in the third seismic topical report.

3.1.1 Frequency-Category-1 Reference Probability

The DOE intends to use a reference mean annual probability of exceedance of 1.0E-03 in determining the Frequency-Category-1 design basis ground motion. The DOE considers that this probability, which corresponds to a 1,000-year return period, represents a conservative quantitative translation of the qualitative frequency description for Category-1 design basis events in the revised 10 CFR 60, i.e., "events that are reasonably likely to occur regularly, moderately frequently, or one or more times before permanent closure of the geologic repository operations area." Assuming a Poisson temporal occurrence model (see Section 3.3.2.2), events with a 1.0E-03/yr recurrence rate would have an 86 percent chance of not occurring, a 13 percent chance of occurring once, and a 1 percent chance of occurring twice in 150 years. For facilities with a 100-year design lifetime, events with this recurrence rate would have a 90 percent chance of not occurring, a 9 percent chance of occurring once, and a 0.4 chance of occurring twice.

An annual occurrence rate of 1.0E-03 for Frequency-Category-1 design basis ground motions are more conservative than what is required by model building codes for ordinary structures, in terms of the annual probability of occurrence of the design basis earthquake, and is comparably conservative in terms of the probability of occurrence during the facility lifetime. The Uniform Building Code (ICBO 1994) and the National Earthquake Hazards Reduction Program (BSSC 1995) both recommend using peak ground motion values that have a 90 percent chance of not being exceeded in 50 years for the life-safety seismic design of new buildings; this corresponds to a return period of about 500 years. DOE Standard 1020-94 (DOE 1994b) is not being applied to the mined geologic disposal system program, but it documents a general DOE policy that a 500-year return period is to be used in establishing design basis ground motions for general facilities. This return period corresponds to an annual exceedance probability of about 2.0E-03 and a 90 percent chance of not occurring during a typical 50-year facility lifetime.

3.1.2 Frequency-Category-2 Reference Probability

For Frequency-Category-2 design basis ground motion, the DOE intends to use a reference mean annual exceedance probability of 1.0E-04. The DOE considers that this mean value is appropriate and conservative based on the observations that (1) it is comparable to the mean exceedance probabilities of the seismic design bases of operating nuclear power reactors in the United States, (2) these accepted reactor design bases and their associated design-acceptance criteria have resulted in acceptably safe seismic designs, (3) design acceptance criteria will be used in repository design that are the same as or comparable to those used in reactor designs, and (4) an operating mined geologic disposal system is inherently less hazardous and less vulnerable to earthquake-initiated accidents than is an operating nuclear power reactor.

3.1.2.1 Comparison with Nuclear Power Reactor Seismic Design Bases

In Regulatory Guide 1.165 (NRC 1997) NRC staff states that a reference median annual exceedance probability of 1.0E-05 will be acceptable for use in determining the safe shutdown earthquake for new nuclear power reactors. The cited rationale for this reference probability is that it is the annual probability level such that 50 percent of a set of currently operating plants (selected by the NRC) has an annual median probability of exceeding the safe shutdown earthquake that is below this level. In other words, 1.0E-05 is the median of the distribution of median exceedance probabilities. The selected plants represent relatively recent designs that used design response spectra in accordance with Regulatory Guide 1.60, *Design Response Spectra for Seismic Design of Nuclear Power Plants* (AEC 1973), or similar spectra. All of the plants selected are located in the central or eastern United States (CEUS). Regulatory Guide 1.165 provides an option for the applicant to use a different reference probability, to be reviewed and accepted on a case-by-case basis, considering the slope of the site-specific hazard curve, the overall uncertainty in hazard estimates, including differences between mean and median hazard estimates, and knowledge of the seismic sources that contribute to the hazard.

In developing Regulatory Guide 1.165, NRC staff considered whether to define the reference probability as a mean or median value. The mean value has the advantage of better reflecting the uncertainty in the seismic hazard evaluation (i.e., it is sensitive to the range of interpretations of seismic source zone configurations, earthquake magnitude recurrence relationships, and ground motion attenuation relationships). However, precisely because the median is less sensitive to uncertainties, it provides a more stable regulatory benchmark than does the mean. Another consideration leading to the staff's preference for the median was the finding that, when median hazard curves were disaggregated, the magnitudes and distances of the controlling earthquakes tended to be more sharply defined and to agree better with the safe shutdown earthquakes of the selected plants than when mean hazard curves were disaggregated (Bernreuter et al. 1996).

For the reasons discussed next, the DOE plans to use mean, rather than median, target annual exceedance probabilities in establishing design basis vibratory ground motions.

To identify the earthquakes that control the Frequency-Category-2 design basis ground motion, the DOE plans to use a mean annual exceedance probability of 1.0E-04. NRC-sponsored research has shown that a mean value of 1.0E-04 corresponds to a median value of 1.0E-05 at sites in the CEUS (NRC 1994b). That is, while 1.0E-05 is the median of the distribution of median exceedance probabilities of the safe shutdown earthquakes of the more recently designed nuclear power reactors in the CEUS, 1.0E-04 is the median of the distribution of means. So, 50 percent of the nuclear power reactors in the selected set have an annual mean probability of exceeding the safe shutdown earthquake that is below this level. Thus, using a mean value of 1.0E-04 to determine the safe shutdown earthquake for a new nuclear power reactor in the CEUS would be risk-consistent with using a median value of 1.0E-05.

In contrast to sites in the CEUS, the equivalency of 1.0E-04 mean and 1.0E-05 median annual probabilities of exceedance does not generally hold in the western United States and is not expected to hold at Yucca Mountain. Because the distributions of probabilistic seismic hazard estimates typically are skewed about the median towards higher probability levels, mean exceedance probabilities usually are greater than median probabilities, and the greater the uncertainty (i.e., spread of the distribution of hazard curves), the greater the difference between the mean and median values. This fact, together with the fact that the uncertainty in seismic hazard evaluations is almost always greater at CEUS sites than at western sites, indicates that mean values normally are closer to median values at western sites than at CEUS sites. Thus, if one were siting a nuclear power reactor at a typical western U.S. site, choosing a mean annual exceedance probability of 1.0E-04 would be consistent with the mean hazard levels associated with the seismic design bases of more recently designed power reactors in the CEUS, but choosing a median annual probability of 1.0E-05 would not be.

As a further check on the reasonableness of using a mean annual exceedance probability of 1.0E-04 as the reference probability for determining the Frequency-Category-2 design basis ground motion, the DOE compiled published probabilistic seismic hazard estimates for the sites of nuclear power plants in the western United States. The objective of the compilation was to determine whether a mean exceedance probability of 1.0E-04/yr is representative of the accepted seismic design response spectra of these plants, as it is for the more recently designed power plants in the CEUS.

Because the shapes of design response spectra rarely match the shapes of uniform hazard spectra, the probabilities of exceeding design response spectra vary with frequency. Therefore, an averaging convention is required to associate a single probability of exceedance with each design response spectrum. To assure comparability of results, this study used the same convention that was used in the study of CEUS plants (NRC 1994b) and that is recommended in Regulatory Guide 1.165 (NRC 1997), i.e., the average of the exceedance probabilities at 5 Hz and 10 Hz[1].

Footnote [1] There is no tacit assumption here that the 5 to 10 Hz frequency range is representative of the natural frequencies of SSCs in a repository. Repository design response spectra will be developed that cover a broad frequency range from 0.33 Hz to more than 20 Hz.

The power plants for which information was compiled are the Diablo Canyon Power Plant (Units 1 and 2) in Port San Luis, California; Palo Verde Nuclear Generating Station (PVNGS) in Wintersburg, Arizona; San Onofre Nuclear Generating Station (Units 2 and 3) in Southern California; Washington Nuclear Plant 2 near Hanford, Washington; and Washington Nuclear Plant 3 at Satsop, Washington. All of these power reactors are currently operating, with the exception of Washington Nuclear Plant 3, which was only partially constructed and which has now been canceled. It is included in this analysis because its seismic design basis was completed and accepted provisionally by NRC staff (NRC 1991a).

Results of the compilation are presented in Appendix C. As shown there the estimated mean annual probability of exceeding the safe shutdown earthquake of each western plant is greater than 1.0E-04/yr, with the single exception of the PVNGS, which is located in a low-seismic-hazard region. The average mean annual probability of exceeding the safe shutdown earthquake of each plant is 2.0E-04, which is twice the value of the reference probability to be used in determining the Frequency-Category-2 design basis ground motion.

3.1.2.2 Conservatism of the Frequency-Category-2 Reference Probability

As noted earlier, the use of NRC-accepted seismic design bases for nuclear power reactors as a benchmark for Frequency-Category-2 design basis ground motion is based on the premise that reactor design bases correspond to acceptable seismic risk levels. The seismic design bases of all nuclear power reactors operating in the United States have been reviewed extensively by NRC staff, using standardized review criteria, and all have been found to satisfy applicable regulatory requirements by NRC licensing boards. In addition, a substantial body of recently developed information indicates that these plants have adequate margins of safety against potential accidents and that they have acceptably safe seismic designs. In June 1991 the NRC requested that its nuclear power reactor licensees perform a plant-specific Individual Plant Examination of External Events (IPEEE) to identify vulnerabilities, if any, to earthquakes, fires, winds, floods, and nearby transportation and other-facility accidents (NRC 1991b). The IPEEE program corroborated the adequacy of the seismic design bases of the Nation's operating nuclear power reactors. For example, specific IPEEE findings for operating reactors in the western United States were as follows:

- In the IPEEE study of the Diablo Canyon Power Plant, Pacific Gas and Electric Company found that the mean core damage frequency due to external events is about 6.7E-05/yr (PG&E 1994) . The component of this risk due to earthquake-initiated accident scenarios was estimated to be 4.0E-05/yr.

- The PVNGS is located in Wintersburg, Arizona, and is operated by the Arizona Public Service Company (APS). The PVNGS site is in a region of low seismic hazard relative to most other regions of the western United States; the PVNGS horizontal design basis response spectrum is anchored at 0.25 g peak ground acceleration (APS 1988). Given the relatively low seismic hazard, APS successfully persuaded NRC staff to have the PVNGS review-level earthquake reduced from 0.5 g (NRC 1991b) to 0.3g. APS elected to conduct a seismic margins analysis for the IPEEE program, rather than a seismic risk assessment. The margins analysis found that at least one safe-shutdown path exists for a peak horizontal ground acceleration in excess of 0.3 g (APS 1995).

- The IPEEE study conducted by Southern California Edison (SCE 1995) for the San Onofre Nuclear Generating Station found that the mean core damage frequency due to external-event initiators is approximately 3.3E-05/yr. The component of this risk due to earthquake-initiated accident scenarios was estimated to be about 1.7E-05/yr.

- In the IPEEE study of the Washington Nuclear Plant 2, the Washington Public Power Supply System (WPPSS 1995) estimated that the mean core damage frequency due to external-event initiators is 2.1E-05/yr and that this risk is dominated by the seismic contribution.

The conservatism of 1.0E-04/yr as a target exceedance probability for the Category-2 design basis ground motion also is based on an assumption that repository design acceptance criteria will reduce the probability of a severe seismically initiated accident below the probability of the design basis ground motions by a "risk-reduction" factor that is comparable to or greater than the factor that is provided by the design acceptance criteria for power reactors. This assumption itself has two bases. The first basis is that the DOE intends to use design acceptance criteria that are the same as or comparable to those used in reactor designs. The DOE has evaluated the NRC standard review plans for the seismic design of nuclear power reactors and has determined that many of the acceptance criteria are applicable to the design of repository surface facilities (see Section 3.2). These facilities are anticipated to include the majority of SSCs important to safety. Acceptance criteria for underground facilities are detailed in Sections 3.3 and 3.4 of this report. The second basis is that a repository is inherently less hazardous and less vulnerable to seismic shaking (or fault displacement) than is an operating nuclear power reactor. As noted by the NRC in the Section-by-Section Analysis of Section 60.136, *Preclosure Controlled Area*, in the Supplementary Information published with the final rule for 10 CFR 60 (61 FR 64257):

> ". . . in comparison with a nuclear power plant, an operating repository is a relatively simple facility in which the primary activities are in relation to waste receipt, handling, storage, and emplacement. A repository does not require the variety and complexity of systems necessary to support an operating nuclear power plant. Further, the conditions are not present at a repository to generate a radioactive source term of a magnitude that, however unlikely, is potentially capable at a nuclear power plant (e.g., from a postulated loss of coolant event). As such, the estimated consequences resulting from limited source term generation at a repository would be correspondingly limited."

In summary, use of a mean annual probability of exceedance of 1.0E-04 as a reference probability for the Frequency-Category-2 vibratory ground motion is quite conservative. This probability is comparable to the probabilities of exceeding the accepted seismic design bases of more recently designed operating nuclear power reactors in the CEUS. A compilation of the mean annual exceedance probabilities of the safe shutdown earthquakes of nuclear power reactors in the western United States indicates that the average mean exceedance probability for this set of reactors exceeds 1.0E-04 by about a factor of two. The DOE considers that use of this value for the preclosure seismic design of the geologic repository operations area is very conservative, given that a repository is inherently less hazardous and less vulnerable to seismic shaking than is an operating nuclear power reactor. The seismic safety of the operating power reactors and, by extension, the adequacy of their seismic design bases, has been confirmed by in-depth, site-specific analyses conducted under the IPEEE program.

3.1.3 Use of Reference Probabilities in Establishing Design Response Spectra

The DOE intends to establish design response spectra that correspond to the Frequency-Category-1 and -2 reference probabilities in a manner similar to that described in Regulatory Guide 1.165 (NRC 1997). This is done by first disaggregating the hazard results to identify the magnitudes and distances of earthquakes that control the hazard at frequencies of engineering interest. Controlling earthquakes will be identified for both of the reference mean annual exceedance probabilities, 1.0E-03 (Frequency Category 1) and 1.0E-04 (Frequency Category 2). Site-specific response spectra will be developed for these controlling earthquakes and will be scaled by the hazard at the reference probability level, at one or more specified frequencies. Finally, smooth design response spectra will be developed that envelope the controlling-earthquake response spectra and that provide sufficient energy over the frequency range of significance to repository SSCs. The details of this process will be developed as part of the development of the repository seismic design and will be fully described in the third seismic topical report.

3.1.4 Use of Reference Probabilities for Other Types of Events

The 10 CFR 60.2 defines Category 1 design basis events as "those natural and human-induced events that are reasonably likely to occur regularly, moderately frequently, or one or more times before permanent closure of the geologic repository operations area," and Category 2 design basis events as "other natural and man-induced events that are considered unlikely, but sufficiently credible to warrant consideration, taking into account the potential for significant radiological impacts on public health and safety." The DOE interprets the frequencies of Frequency Category 1 events (using the DOE's terminology) to be one every 100 years for infrastructure systems (ventilation, surface facilities, etc.) and one every 150 years for ground support systems; events with frequencies less than these values but greater than one every million years are interpreted to be Frequency Category 2 events. This interpretation is consistent with the NRC's statement (61 FR 64257) that the upper probability bound for Category 2 design basis events is roughly 1.0E-02 per year and the lower bound is on the order of 1.0E-06 per year. To ensure conservatism and consistency in the preclosure repository seismic design, the DOE has adopted lower probability levels for design basis seismic loads, as noted above (i.e., annual probabilities of 1.0E-03 and 1.0E-04 for Frequency-Category-1 and -2 vibratory ground motions, respectively, and 1.0E-04 and 1.0E-05 for Frequency-Category-1 and -2 fault displacements, respectively).

The reference probabilities proposed here for seismic loads are not intended to be applicable to other types of design basis external events such as severe winds, fires, or floods, or to design basis internal events. The probabilities for seismic loads are based on professional practice in seismic design, engineering judgment, and industry-wide experience in the licensing of nuclear power reactor seismic designs. Other criteria can be expected to apply to other types of design basis events, considering the degree of uncertainty in characterizing the frequency and severity of events; the potential consequences of exceeding design basis events; the incremental cost of increasing the basis for design; the methodology used to identify the design basis events; and established standards, codes, guidelines, and professional practices.

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