Division of High-Level Waste Repository Safety - Interim Staff Guidance
HLWRS-ISG-01 REVIEW METHODOLOGY FOR SEISMICALLY INITIATED EVENT SEQUENCES

DRAFT

Introduction:

The purpose of this Interim Staff Guidance is to supplement the Yucca Mountain Review Plan (YMRP)[1] (Ref.1) for review of seismically initiated event sequences in the preclosure safety analysis. The applicable sections of the YMRP amplified by the guidance are 2.1.1.4.2, “Review Method 2 Categories 1 and 2 Event Sequences”, and 2.1.1.4.3, “Acceptance Criterion 2 for Identification of Categories 1 and 2 event sequences”. This guidance provides an example methodology to review seismically initiated event sequences, in context of the preclosure safety analysis, for compliance with performance objectives in 10 CFR 63.111(b)(2). The methodology considers the likelihood of seismic initiating events and event sequences at the site and structural fragility of Structures, Systems, and Components (SSCs) Important to Safety (ITS), to estimate probability of failure of SSCs ITS and frequency of occurrence of event sequences. This guidance was developed to take advantage of improvements in probabilistic seismic hazard analyses and performance-based safety assessments, thus differing from the design-based and deterministic hazard criteria previously used for licensing of nuclear facilities, especially nuclear power plants.

Discussion:

Regulations for licensing the proposed geological repository at Yucca Mountain, Nevada, are contained in 10 CFR Part 63. The preclosure compliance requirements in Part 63 are performance-based. Instead of specifying specific design loads with corresponding codes/standards, regulations in 10 CFR 63.111 for the geological repository operations area (GROA) specify a performance-based standard as radiological dose limits to the public for Categories 1 and 2 event sequences. Category 1 event sequences are those that are expected to occur one or more times before permanent closure of the GROA, whereas Category 2 event sequences are those other event sequences that have at least one chance in 10,000 of occurring before permanent closure of the GROA. Event sequences with the probability of occurrence less than that of a Category 2 event sequence are screened out.

To meet the performance objectives of 10 CFR 63.111 for seismic hazard, the preclosure safety analysis must include a systematic examination of the site, characterization of the seismic hazard, resulting event sequences, and potential radiological exposures to the public. Based on the review of these event sequences, and the potential release of radioactive material and estimated doses, SSCs ITS that are relied on to prevent potential event sequences or mitigate their consequences must be evaluated to demonstrate their ability to perform intended safety functions under seismic loads.

The probability of occurrence of seismic initiating events and the failure probabilities of SSCs ITS need to be considered to demonstrate that SSCs ITS will perform their intended safety functions. The probability of occurrence of an event sequence leading to an SSC ITS failure, or

[1]U. S. Nuclear Regulatory Commission, *Yucca Mountain Review Plan*, NUREG-1804, Revision 2, Final Report, July, 2003.

seismic performance, is determined by convolution[2] of the mean seismic hazard curve with the mean conditional failure probabilities (i.e., fragility) of the SSCs ITS. The mean fragility curve for an SSC ITS may be estimated using: (1) probability density functions for controlling parameters in a Monte Carlo analysis; (2) simplified methods outlined in Section 4 of Electric Power Research Institute, TR-103959 (Ref. 2); or (3) other methods that capture appropriate variability and uncertainty in parameters used to estimate the capacity of the SSCs ITS to seismic events.

This ISG describes one method that staff may use to review the seismic performance of SSCs ITS and frequency of occurrence of seismic event sequences, as required by the performance objectives in 10 CFR 63.111(b)(2). This methodology is similar to the one outlined in ASCE 43-05 (Ref. 3). NRC has accepted this methodology to support licensing of the Mixed-Oxide Fuel Fabrication Facility at the Savannah River Site in South Carolina (Section 5.1.6.1 of Ref. 4). Application of the methodology described in ASCE 43-05 (Ref. 3) and the scope of seismic design and analysis for the GROA must be consistent with the Part 63 preclosure safety analysis requirements. The U. S. Department of Energy (DOE) may, however, use alternative methods to demonstrate compliance with the Part 63 preclosure safety analysis requirements for analysis of event sequences.

The review methodology described herein is based on evaluating event sequences for seismically initiated events and identifying SSCs ITS for seismic performance evaluation. The first step in estimating the probability of occurrence of seismic event sequences is to assess the seismic performance of the individual SSC ITS. For example, to obtain the mean fragility curve of the individual SSC ITS, the median capacity ($C_{50\%}$) and the composite logarithmic standard deviation (β) should be estimated using transparent technical bases. Failure criteria used for estimating the fragility curves should be consistent with the SSCs ITS functional requirements. The mean annual failure probability of the individual SSCs ITS can then be obtained by convolving the mean seismic hazard curve at the site, and the mean fragility curve. An example described in Appendix A of this ISG illustrates this general methodology.

If the annual probability of failure values of individual SSCs ITS for seismically initiated event sequences, estimated using the methodology discussed above, is less than 1 in 10,000 during the preclosure period, as defined in 10 CFR 63.2 for Category 2 event sequences, the SSC ITS is considered to perform its intended safety function and meets 10 CFR 63.111. If, however, the annual probability of failure of the individual SSCs ITS for seismically initiated event sequences is greater than or equal to 1 in 10,000 during the preclosure period, DOE may demonstrate compliance with 10 CFR 63.111 by showing that the probability of occurrence of each of the seismic event sequences containing the SSC ITS is less than 1 in 10,000 during the preclosure period. Alternatively, DOE may show that the dose consequence to the public at the site boundary from the event sequence is less than the dose limits in 10 CFR 63.111(b)(2). Appendix B of this Interim Staff Guidance demonstrates an example procedure for evaluating seismic event sequences, when the probability of failure of individual SSC ITS is greater than or equal to 1 in 10,000 during the preclosure period.

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[2]The term “convolution” is used to indicate summation or integration of the probability of failure over the range of the seismic hazards and is consistent with the American Society of Civil Engineers Standard 43-05 (Section C 2.2 of Ref. 3).

Regulatory Basis:

1. *Preclosure safety analysis.* A preclosure safety analysis of the geologic repository operations area that meets the requirements specified at § 63.112 must be performed. This analysis must demonstrate that: (1) The requirements of § 63.111(a) will be met; and (2) The design meets the requirements of § 63.111(b) [10 CFR 63.111(c)].

2. The preclosure safety analysis of the geologic repository area must include an analysis of the performance of the structures, systems and components to identify those that are important to safety. This analysis identifies and describes the controls that are relied on to limit or prevent potential event sequences or mitigate their consequences. This analysis also identifies measures taken to ensure the availability of safety systems. The analysis must include, but not necessarily be limited to, consideration of the ability of structures, systems and components to perform their intended safety functions, assuming the occurrence of event sequences. [10 CFR 63.112(e)(8)].

3. Those event sequences that are expected to occur one or more times before permanent closure of the geologic repository operations area are referred to as Category 1 event sequences. Other event sequences that have at least one chance in 10,000 of occurring before permanent closure are referred to as Category 2 event sequences. [10 CFR 63.2 *Event Sequences*].

4. During normal operations, and for Category 1 event sequences, the annual Total Effective Dose Equivalent (TEDE) to any real member of the public located beyond the boundary of the site may not exceed the preclosure standard specified at § 63.204 [10 CFR 63.111(a)].

5. The geological repository operations area must be designed so that, taking into consideration any single Category 2 event sequence and until permanent closure has been completed, no individual located on, or beyond, any point on the boundary of the site will receive, as a result of the single Category 2 event sequence, the more limiting of a TEDE of 0.05 Sv (5 rem), or the sum of the deep dose equivalent and the committed dose equivalent to any individual organ or tissue (other than the lens of the eye) of 0.5 Sv (50 rem). The lens dose equivalent may not exceed 0.15 Sv (15 rem) and the shallow dose equivalent to skin may not exceed 0.5 Sv (50 rem) [10 CFR 63.111(b)(2)].

Technical Review Guidance and Recommendations:

The following changes to the YMRP are recommended:

1. Revise Section 2.1.1.4.2, "Review Methods, **Review Method 2,** *Categories 1 and 2 Event Sequences"*, as follows:

    Page 2.1-26, after 5th paragraph: Add the following:

    Verify that the seismic hazard for the site has been reviewed as required in Section 2.1.1.3, and is found to be acceptable for use in estimating the probabilities of earthquake-induced seismic loads, and the design basis of structures, systems, and components in Section 2.1.1.7.

Verify that, in calculating the probability of occurrence of seismic event sequences, DOE has considered the seismic performance of SSCs ITS, using appropriate mean seismic hazard input, along with the mean conditional failure probabilities (i.e., fragility) of structures, systems, and components, important to safety.

2. Revise Section 2.1.1.4.3, “Acceptance Criteria, **Acceptance Criterion 2,** *Categories 1 and 2 Event Sequences are Adequately identified”,* as follows:

Page 2.1-27, after Item (3): Add the following and renumber the subsequent items:

(4) The U. S. Department of Energy has considered uncertainties in the supporting numerical models, structural system parameters, and demands, in calculating the probabilities of occurrence of seismically initiated event sequences.

Page 2.1-27, after Item (5): Add the following and renumber the subsequent items:

(6) The U. S. Department of Energy has appropriately considered the mean probability of earthquake-induced ground motions, and the mean probability of failure in response to a given seismic hazard for SSCs ITS in calculating the probability of seismically initiated event sequences.

References

1. U. S. Nuclear Regulatory Commission, *Yucca Mountain Review Plan*, NUREG-1804, Revision 2, Final Report, July, 2003.

2. Electric Power Research Institute, *Methodology for Developing Seismic Fragilities*, EPRI TR-103959, June 1994.

3. American Society of Civil Engineers, *Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities*, ASCE/SEI 43-05, 2005.

4. U.S. Nuclear Regulatory Commission, *Final Safety Evaluation Report on the Construction Authorization Request for the Mixed-Oxide Fuel Fabrication at the Savannah River Site, South Carolina*, NUREG-1821, 2005.

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Glossary

Appendices

Appendix A Example Methodology for Computing SSC ITS Probability of Failure during a Seismic Event

Appendix B Example Methodology for Evaluation of Complete Event Sequences

GLOSSARY

EVENT SEQUENCE: *“Event sequence* means a series of actions and/or occurrences, within the natural and engineered components of a geologic repository operations area, that could potentially lead to exposure of individuals to radiation. An event sequence includes one or more initiating events and associated combinations of repository system component failures, including those produced by the action or inaction of operating personnel. Those event sequences that are expected to occur one or more times before permanent closure of the geologic repository operations area are referred to as Category 1 event sequences. Other event sequences that have at least one chance in 10,000 of occurring before permanent closure are referred to as Category 2 event sequences” [10 CFR 63.2 *Event Sequences*].

FRAGILITY: *Fragility* of a structure, system, or component is defined as the conditional probability of its failure, given a value of the response parameter, such as stress, bending moment, and spectral acceleration.

IMPORTANT TO SAFETY (ITS): “With reference to structures, systems, and components, *important to safety* means those engineered features of the geologic repository operations area whose function is: (1) to provide reasonable assurance that high-level waste can be received, handled, packaged, stored, emplaced, and retrieved without exceeding the requirements of § 63.111(b)(1) for Category 1 event sequences; or (2) to prevent or mitigate Category 2 event sequences that could result in radiological exposures exceeding the values specified at § 63.111(b)(2) to any individual located on or beyond any point on the boundary of the site” [10 CFR 63.2 *Important to Safety*].

PRECLOSURE SAFETY ANALYSIS (PCSA): *“Preclosure safety analysis* means a systematic examination of the site, the design, and the potential hazards, initiating events and event sequences, and their consequences (e.g., radiological exposures to workers and the public). The analysis identifies structures, systems, and components important to safety” [10 CFR 63.2 *Preclosure Safety Analysis*].

SEISMIC HAZARD CURVE: *Seismic hazard curve* is a graph showing the ground motion parameter of interest, such as spectral acceleration at a given frequency, plotted as a function of annual probability of exceedance.

SEISMIC PERFORMANCE: *Seismic performance* of structures, systems, and components means their ability to perform intended safety functions during a seismic event. Seismic performance of structures, systems, and components is expressed as annual probability of exceeding a specified limit condition (stress, displacement, or collapse). This is also referred to as the probability of failure, or probability of unacceptable performance, P_F.

STRUCTURES, SYSTEMS, AND COMPONENTS (SSCs): A *structure* is an element, or a collection of elements, to provide support or enclosure, such as a building, free-standing tanks, basins, dikes, or stacks. A *system* is a collection of components assembled to perform a function, such as piping, cable trays, conduits, or heating, ventilation, and air-conditioning (HVAC). A *component* is an item of mechanical or electrical equipment, such as a pump, valve, or relay, or an element of a larger array, such as a length of pipe, elbow, or reducer.

APPENDIX A
EXAMPLE METHODOLOGY FOR COMPUTING SSC ITS PROBABILITY OF FAILURE DURING A SEISMIC EVENT

The example shown below illustrates how the probability of failure of a structure, system, or component (SSC) important to safety (ITS) may be estimated, based on a seismic hazard curve and a fragility curve of the SSC. The evaluation typically would be performed at appropriate structural frequencies, based on the dynamic characteristics of the SSC ITS. It should be noted that the example evaluation is performed at 10 hertz (Hz) structural frequency.

- The seismic performance or failure probability of an SSC ITS, P_F, is estimated by convolving the mean seismic hazard, *H(a)* (i.e., annual probability of exceedance of ground motion level, *a*) and the mean fragility, $P_F(a)$, (i.e., conditional probability of failure, given the ground motion level, *a*) curves, as shown below (Ref. 3):

$$P_F = -\int_0^\infty P_F(a)\left(\frac{dH(a)}{da}\right) da$$

or

$$P_F = \int_0^\infty H(a)\left(\frac{dP_F(a)}{da}\right) da$$

The convolution can be performed numerically or using a closed-form solution:

- Hypothetical seismic hazard curve *H(a)* used for this example is shown in Figure A-1.

- The mean fragility curve of an SSC ITS for a defined failure mode is typically defined as being lognormally distributed, and can be expressed in terms of a median capacity level, $C_{50\%}$, and a composite logarithmic standard deviation, β. The technical basis for the development of the median capacity and the composite logarithmic standard deviation, β, should be available for staff review.

    For the current example, the median capacity, $C_{50\%}$, is assumed to be 6.9 g, where "g" is the acceleration due to gravity, and the logarithmic standard deviation, β , is assumed to be 0.35.

    See Figure A-2 for the fragility curve.

- For numerical convolution, the hazard curve is discretized into equal small intervals that assume constant acceleration through each interval. The seismic performance is obtained by the product of the hazard exceedance interval and the fragility value corresponding to the acceleration for each interval, and summed over the entire hazard curve.

Using this method, the annual probability of failure of the example SSC ITS obtained by numerical convolution is 1.5 x10^{-6}.

- For the closed-form solution, the seismic hazard curve is assumed to be linear in log-log scale and is approximated by a power law (Section 2.2.1.2 of Ref. 3):

$$H(a) = K_1 a^{-K_H} ,$$

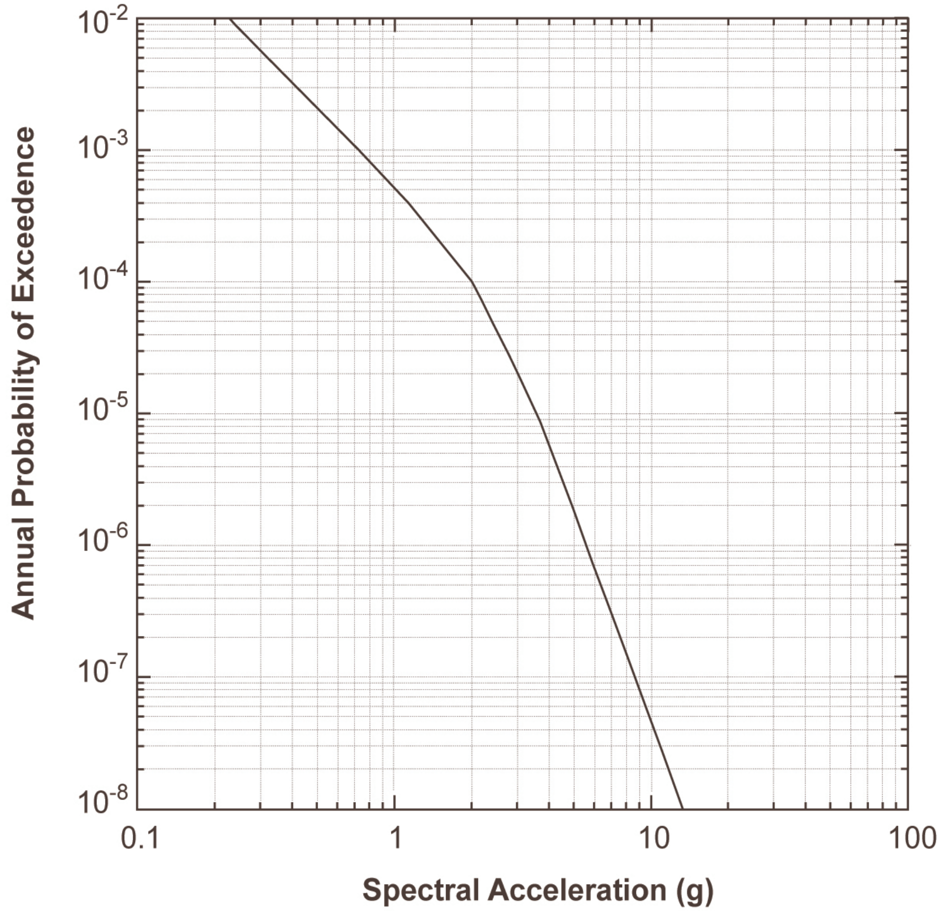
where K_1 is a constant (9 x 10^{-3} for this case), and K_H is the slope parameter given by K_H = 1/log (A_R) = 5.30. A_R is the ratio of the spectral acceleration (SA) corresponding to ten-fold reduction in exceedance probability, (i.e., $A_R = SA_{0.1H(a)}/SA_{H(a)}$). The slope used for this example is between probabilities of exceedance of 10^{-6} and 10^{-5}.

The annual probability of failure of the SSC ITS using the closed-from solution can be derived from Equations C2-7 and C2-8 of ASCE 43-05 (Ref. 3), and is given by

$$P_F = K_1 (C_{50\%})^{-K_H} e^{0.5(K_H \beta)^2} .$$

Using the same $C_{50\%}$ and β values as for the numerical convolution, the annual probability of failure of the example SSC ITS calculated using the closed-form solution method is 1.8 x 10^{-6}, in contrast to 1.5 x 10^{-6} by numerical convolution.

Assuming a 100-year preclosure period, a Category 2 event sequence annual probability of occurrence would be equal to or greater than 10^{-6}. Because the example SSC ITS failure probability exceeds 10^{-6} per year, the event sequences that include this SSC ITS should be evaluated further to calculate the probability of occurrence of the entire event sequence. An example methodology to calculate the event sequence probability is described in Appendix B of this ISG.



254 **Figure A-1 Hypothetical Seismic Hazard Curve for the 10 Hz Spectral Acceleration**

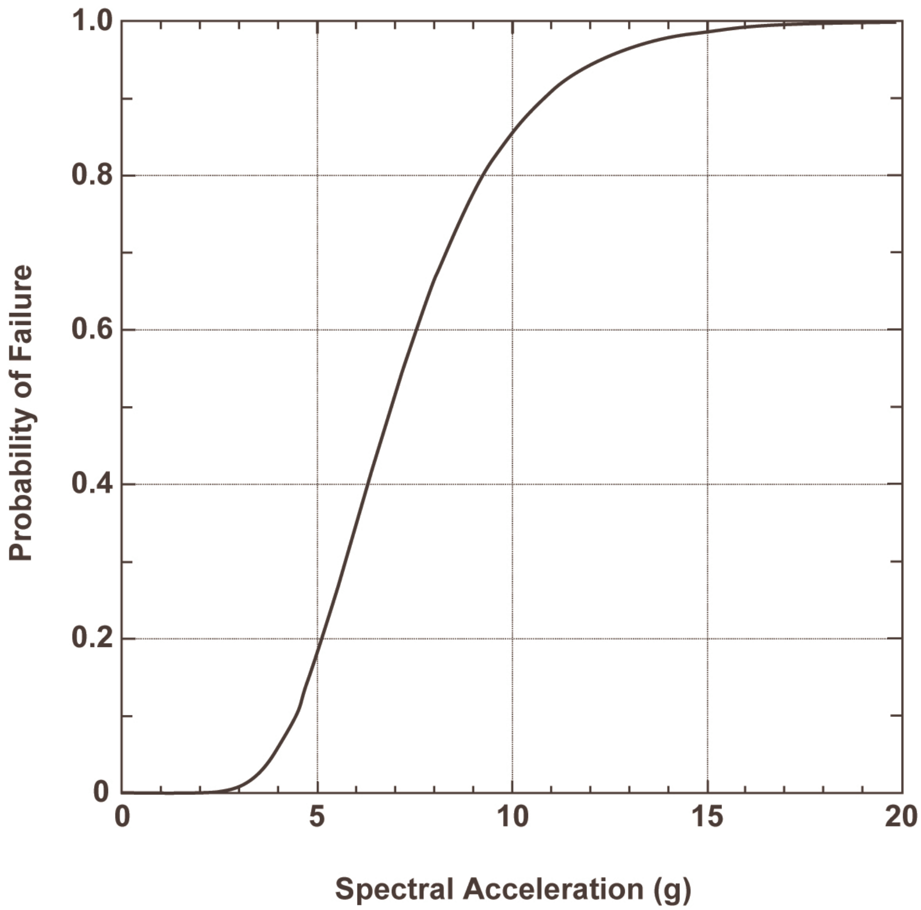


Figure A-2 Example Seismic Fragility Curve for the 10 Hz Spectral Acceleration

Appendix B
Example Methodology for Evaluation of Complete Event Sequences

This appendix describes a method to evaluate the probability of occurrence of a seismically induced event sequence. The procedure is based on the failure probabilities of structures, systems, and components (SSCs), important to safety (ITS) during a seismic event, as described in Appendix A. The evaluation typically would be performed at appropriate frequencies, based on the dynamic characteristics of the SSC ITS. It should be noted that the example evaluation is performed at 10 hertz (Hz) structural frequency.

A) An example operation involving movement of canisters in a conceptual waste handling facility:
   - A bridge crane is used to transfer canisters.
   - Facility structure, which consists of shear walls and roof slabs, is designed to provide confinement of any release of radioactive material from damaged canisters.
   - Heating, Ventilation, and Air-Conditioning (HVAC) and High-Efficiency Particulate Air (HEPA) system provides filtration of radionuclide particulates.

B) Potential sequence of events resulting from a seismically initiated event in this example operation are:
   - Conditional failure of components in the crane system during a seismic event may initiate event sequences.
   - Canister is assumed to drop, and fails to perform the intended safety functions resulting in a release of radionuclide material.
   - Conditional failure of the concrete shear wall of the facility structure during the seismic event may result in loss of confinement.
   - Conditional failure of HVAC duct anchor system during the seismic event may result in loss of confinement.

C) Figure B-1 shows a simple event tree depicting the hypothetical sequence of events that could potentially lead to release of radioactive material to the environment.
   - Event sequence 2 results in a mitigated release (e.g., radiological gases) because the HVAC system performs its intended safety functions during the seismic event.
   - Event sequences 3 and 4 could result in release of radioactive materials, if the SSC ITS fails to perform its intended safety function.

D) The following steps are used to estimate the annual probability of occurrence of each hypothetical event sequence that may lead to release of radioactive materials.

   1. The median capacity, $C_{50\%}$, and logarithmic standard deviation, β, for SSCs ITS at 10-Hz structural frequency, are assumed to be:

      Crane system, CRN_COMP - $C_{50\%}$ = 6.3 g, β=0.40,
      Concrete shear wall for facility structure, STR_SHWL - $C_{50\%}$= 7.2 g, β =0.35,
      HVAC duct anchor system, HVAC_ANC - $C_{50\%}$= 5.7 g, β= 0.45,

      where "g" is the acceleration due to gravity.

2. Based on the median capacities and logarithmic standard deviations listed in step 1, annual probabilities of failure, P_F, for the individual SSC ITS, are estimated using the procedure in Appendix A:

   Crane system, CRN_COMP: 3.2 x 10^{-6}.
   Concrete shear wall for facility structure, STR_HWL: 1.2 x 10^{-6}.
   HVAC duct anchor system, HVAC_ANC: 6.7 x 10^{-6}.

Based on this example analysis, the crane components, concrete shear wall, and HVAC duct anchor system each have annual probabilities of failure greater than 10^{-6} for a Category 2 event sequence, assuming a 100-year preclosure period. Therefore, event sequences that include these SSCs ITS need to be evaluated further.

As shown in figure B-1, in event sequence 3, unmitigated release may occur if both the crane system fails and drops the canister, and the HVAC duct anchor system supporting the duct fails. In this event sequence, the fragilities of the crane system and the HVAC duct anchor system are dependent on the spectral acceleration of the seismic event. However, the fragilities of these two systems are independent of each other. Therefore, the combined fragility of the two systems in the event sequence can be obtained by multiplying fragilities of each system at various seismic spectral acceleration values. To determine the probability of occurrence of the event sequence, the combined fragility curves for both SSCs ITS must then be convolved with the hazard curve. For example, at a spectral acceleration of 8.3 g (Fig. B-2) for event sequence 3, the probabilities of failure of the crane and the HVAC anchor system are 0.75 and 0.8, respectively. This would yield the combined failure probability of both SSCs ITS of 0.75 x 0.8 = 0.6. Using this procedure at various spectral acceleration values, the fragility curve for the event sequence was obtained as shown in Figure B-2. The fragility curve for the event sequence was then convolved with the hazard curve in Figure A-1 to obtain the annual probability of occurrence of the event sequence of 8.4 x 10^{-7}, which is less than 10^{-6} for a Category 2 event sequence, assuming a 100-year preclosure period (see Appendix A).

Similarly, in event sequence 4, unmitigated release may occur if both the crane system fails and drops the canister, and the concrete shear wall fails to confine radioactive material. In this event sequence, the fragilities of the crane system and the concrete shear wall can be combined, as described for event sequence 3 (see Figure B-3 for example fragility curves of the SSCs ITS in this event sequence). The resulting annual probability of occurrence of the event sequence is 3.8 x 10^{-7}, which is less than 10^{-6} for a Category 2 event sequence, assuming a 100-year preclosure period (see Appendix A).

Although evaluation of individual SSC ITS in an event sequence may indicate a probability of failure of greater than 10^{-6} during a seismic event, this example shows that appropriate consideration of these SSCs ITS jointly may result in an event sequence probability of occurrence less than 10^{-6}, which is not a credible event sequence for the preclosure safety analysis. If the event sequence annual probability of occurrence was greater than 10^{-6}, it would be considered a Category 2 event sequence. In this case, a radiological consequence assessment would be needed to demonstrate that the numerical dose limits of 10 CFR 63.111(b)(2) are not exceeded.

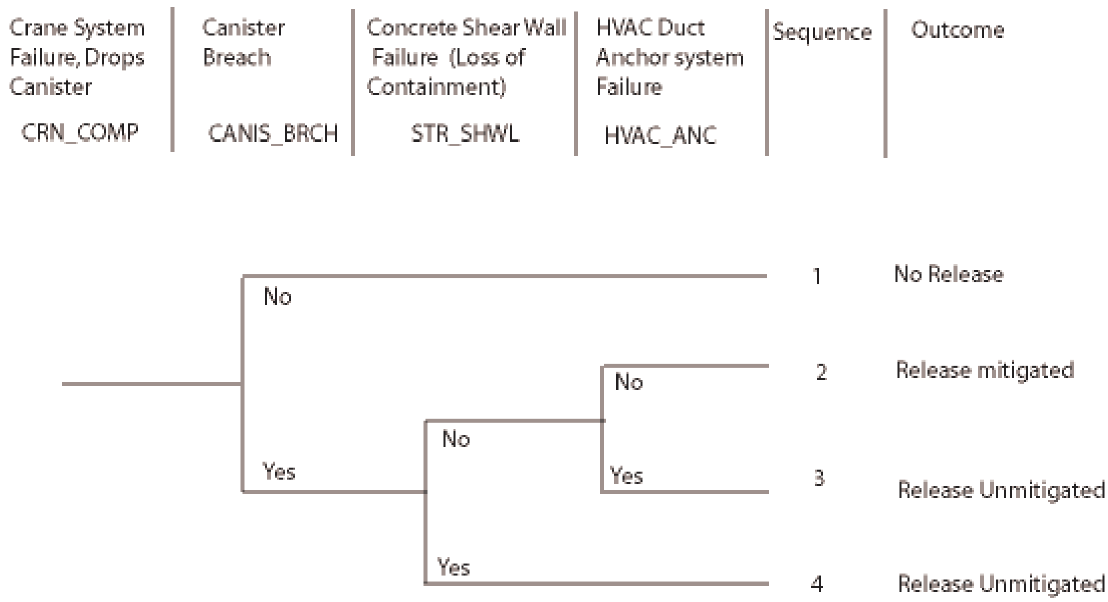


Figure B-1 Seismically Initiated Event Sequences

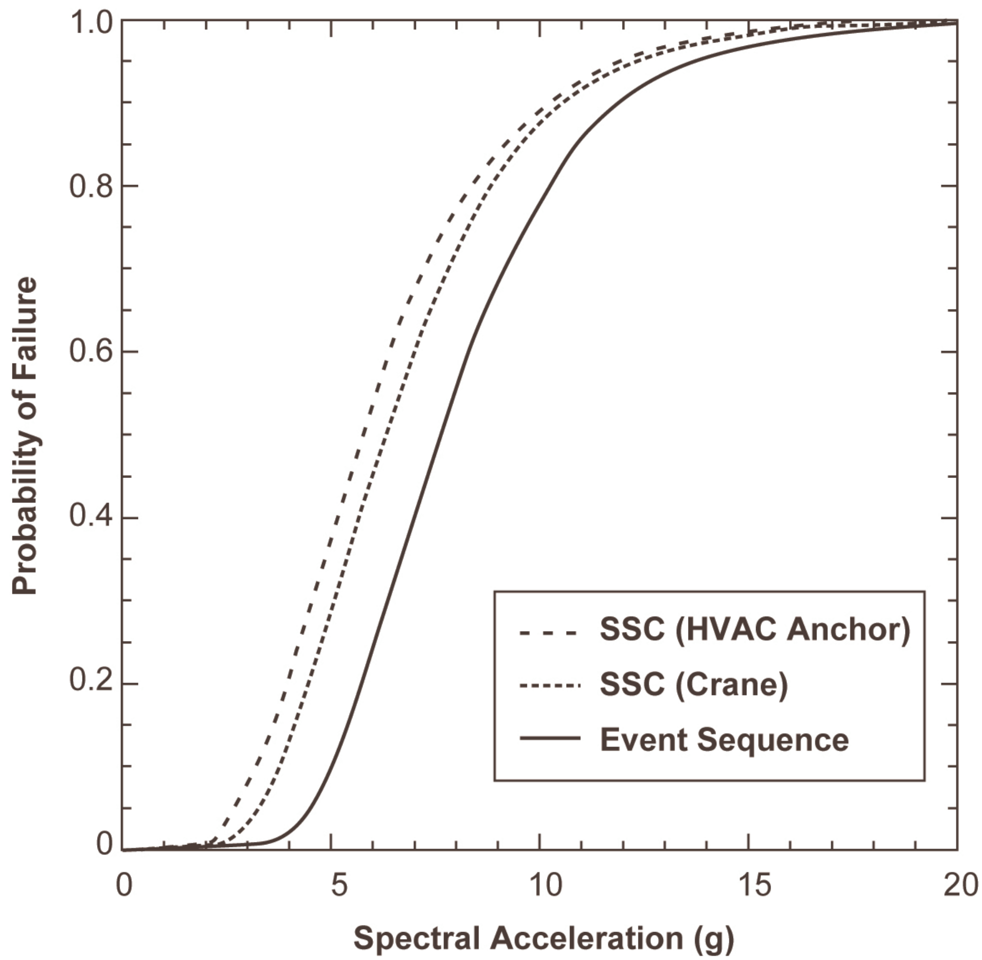
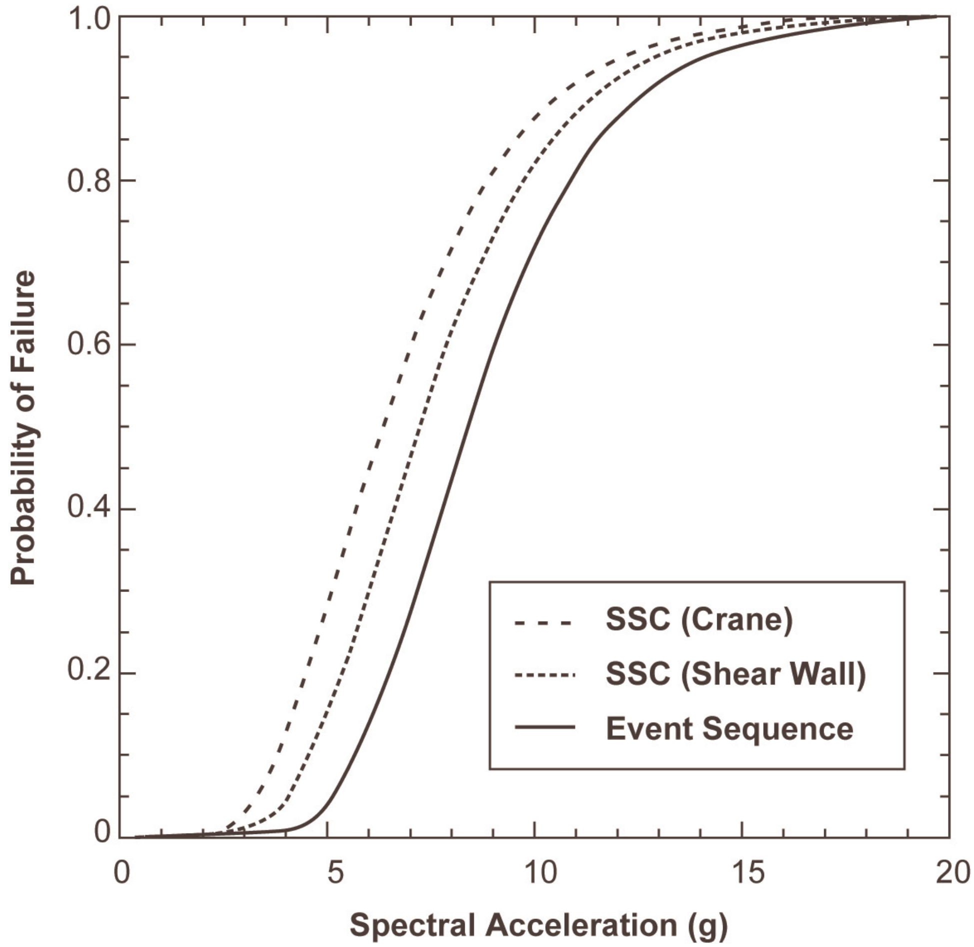


Figure B-2 Mean Fragility Curves for Event Sequence 3



341 **Figure B-3 Mean Fragility Curves for Event Sequence 4**

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Appendices

Appendix A Example Methodology for Computing SSC Probability of Failure during a Seismic Event

Appendix B Example Methodology for Evaluation of Complete Event Sequences

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