Seismic probabilistic risk assessment for seismically isolated safety-related nuclear facilities

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ABSTRACT

In the United States, seismic probabilistic risk assessment is performed on nuclear power plant (NPP) designs to calculate mean annual frequencies of unacceptable performance, including core damage and large early release (of radiation). Seismic (base) isolation is a viable strategy to protect NPPs from extreme earthquake shaking but it has not yet been employed in the United States, in part due to a lack of clear regulatory guidance. Guidance and standards for seismic isolation of NPPs are now becoming available, but they do not explicitly address risk calculations.

This paper presents seismic risk calculations for safety-related nuclear structures, including NPPs, isolated using nonlinear bearings, with a focus on assessing risk associated with the isolation system and the safety-related umbilical lines. Fragility curves are developed for the isolation systems and umbilical lines of NPPs located at eight sites of nuclear facilities across the United States assuming that the performance goals outlined in a forthcoming NUREG/CR focusing on seismic isolation and Chapter 12 of ASCE Standard 4-16 are satisfied. Risk is computed for isolation systems in NPPs with and without a stop. The mean annual frequency of unacceptable performance at each site is less than 1×10^{-6} (1×10^{-5}) following the guidance (requirements) set forth in the NUREG/CR (ASCE 4) if a stop or displacement restraint is provided.

Three strategies for reducing the calculated mean annual frequency of unacceptable performance are investigated and quantified, namely, 1) testing more prototype isolators to achieve greater confidence, 2) testing isolators for a larger displacement and corresponding axial force at a given confidence level, and 3) providing a stop. The annual frequency of unacceptable performance of the isolation system (and umbilical lines) is greater than 1×10^{-6} (the assumed target annual frequency of unacceptable performance), if the isolation system is designed per the forthcoming NUREG/CR and a stop is not provided, even though there is considerable reduction in risk if the

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isolators are tested for a greater displacement (and corresponding axial force) and/or with a greater confidence level than that required by the forthcoming NUREG/CR. The risk is well below 1×10^{-6} if a stop is provided. A stop is needed to achieve the corresponding target annual frequency of unacceptable performance of 1×10^{-5} if the isolators (and umbilical lines) are designed and tested per ASCE 4-16. The risk calculations were performed setting the design factor (the factor by which the ordinates of the design basis response spectrum per the ASCE 4-16 and ASCE 43-05 are increased) equal to 1.0. Because the achieved annual frequency of unacceptable performance of the isolation system (and umbilical lines) is less than the corresponding target set in the forthcoming NUREG/CR (a United States Nuclear Regulatory Commission report) and ASCE Standard 4-16 (that has developed from United States Department of Energy guidance), if the earthquake risk is dominated by horizontal ground shaking and a stop is provided, the design factor can be set equal to 1.0 for a seismically isolated NPP.

1. Introduction

The seismic hazard for the analysis and design of ***conventionally-founded*** nuclear structures is defined as the product of a uniform hazard response spectrum (UHRS) at a seismic design category (SDC)-based mean annual frequency of exceedance (MAFE) and a design factor (e.g., Regulatory Guide (RG) 1.208 (USNRC, 2007a), ASCE (2005) and ASCE (2016)). Two levels of seismic hazard will be considered for the analysis and design of seismically ***isolated*** nuclear structures: 1) design basis earthquake ground motion per ASCE 43 (ASCE, 2005) and ASCE 4 (ASCE, 2016) or a ground motion response spectrum (GMRS) per RG 1.208, and 2) beyond design basis shaking per ASCE 4 or the forthcoming NUREG/CR (Kammerer *et al.*, forthcoming). The probabilities of the isolated superstructure impacting the stop, and/or of the loss of either function of the isolation system (loss of axial load carrying capacity at a specified displacement) or the umbilical lines, at the two shaking levels are required to be smaller than specified values.

In this paper, seismic hazard definitions for the conventionally founded and seismically isolated NPPs are reviewed. The mean annual frequencies of unacceptable performance are calculated for hypothetical NPPs at eight sites across the United States, representing regions of low, moderate, and high seismic hazard, assuming that the performance goals outlined in the forthcoming NUREG/CR are satisfied. Parallel calculations are performed for the eight sites with the performance goals defined per ASCE 4-16. The purpose of these calculations is three-fold, namely, 1) provide a roadmap for an applicant to calculate the earthquake risk associated with a seismic isolation system with a given horizontal displacement capacity, 2) provide the United States Nuclear Regulatory Commission (USNRC) and the United States Department of Energy (DOE) with insight into the risk associated with a seismic isolation system tested at different displacements with different confidence levels, and with and without a stop present, and 3) determine the design factor for seismically isolated NPPs.

2. Seismic hazard at the site of nuclear facilities in the United States

Fig. 1 presents seismic hazard curves (spectral acceleration versus MAFE) at eight sites of nuclear facilities across the United States (see Fig. 2) for four periods (0.1 s, 0.2 s, 1 s and 2 s) and 5% damping. The data are downloaded from the United States Geological Survey (USGS) website: http://geohazards.usgs.gov/hazardtool/application.php (accessed on December 30, 2014) and are associated with a shear wave velocity in the upper 30 m of the soil column of 760 m/s.

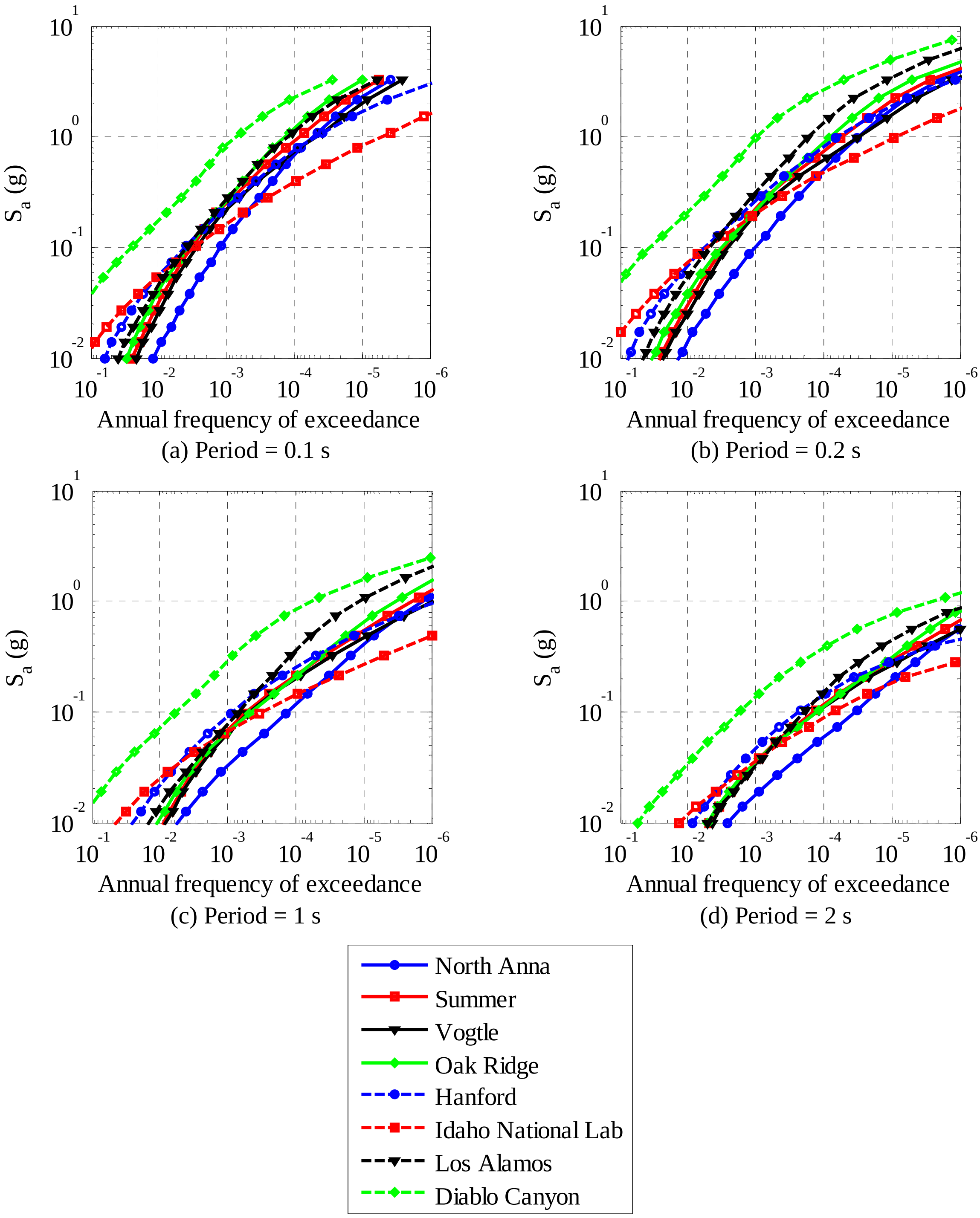

Fig. 1. Seismic hazard curves for eight sites of nuclear facilities in the United States and 5% damping.

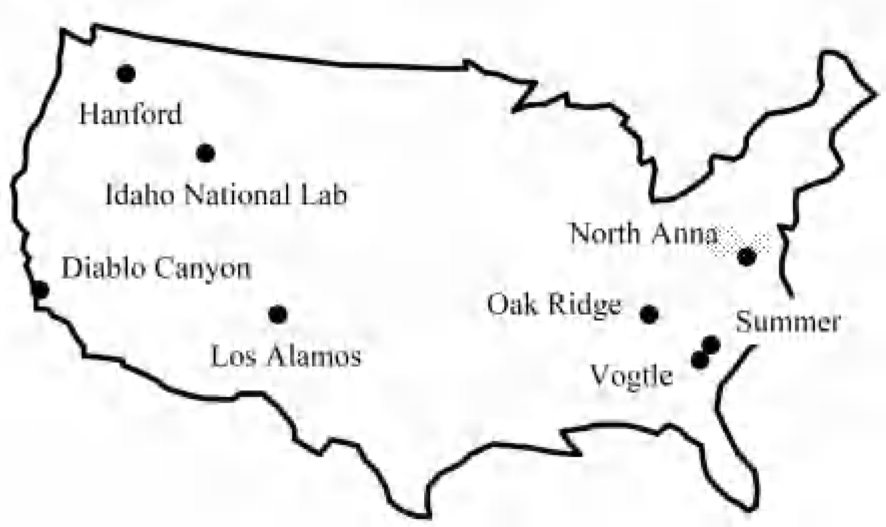

Fig. 2. Sites of eight nuclear facilities in the United States.

3. Conventional nuclear power plants

3.1. Seismic hazard definition

The seismic hazard for the analysis and design of a conventionally founded nuclear structure is defined in ASCE 43. This risk-oriented definition of hazard was first implemented in the United States DOE guideline "Natural phenomena hazards design and evaluation criteria for Department of Energy facilities" (DOE, 1994). The design response spectrum, DRS, is obtained by multiplying the ordinates of the UHRS, which is established for by a design factor, DF:

$$DRS = DF \times \mathrm{UHRS} \tag{1}$$

where the UHRS is established by probabilistic seismic hazard analysis for a specified annual frequency of exceedance, H_D. For a non-isolated nuclear structure, the UHRS is increased by DF to achieve a target performance goal P_F. ASCE Standard 43-05 provides an expression to compute DF, namely,

$$DF = \max\left(1.0,\ 0.6\left(A_R\right)^{\alpha}\right) \tag{2}$$

where α is a parameter that depends on the SDC, and A_R is the slope of the seismic hazard curve:

$$A_R = \frac{SA_{0.1H_D}}{SA_{H_D}} \tag{3}$$

where $SA_{0.1H_D}$ and SA_{H_D} are 5% damped spectral accelerations corresponding to annual frequencies of exceedance of 0.1 H_D and H_D, respectively.

Fig. 1 shows that the values of A_R depend strongly on the site and the value of MAFE considered. North Anna is an Eastern US site; Hanford is a Western US site. For a period of 0.1 s and MAFE of 10^{-2} (10^{-3}, 10^{-4}), A_R for these two sites are 9.8 (5.6, 3.4) and 4.2 (3.2, 2.3), respectively. The spectral accelerations at MAFE of 10^{-2}, 10^{-3} and 10^{-4} are computed assuming a linear variation of spectral acceleration with MAFE in logarithmic space between adjacent data points (e.g., ASCE (2005)).

The values of A_R for all eight sites are listed in Table 1. Focusing on an MAFE of 10^{-4}, which is the basis for the design of NPPs in the United States, it is clear that A_R is greater in the eastern and central United States than in the western United States, irrespective of period. For conventionally founded nuclear facilities, the data at periods of 0.1 s and 0.2 s are relevant for calculating the DF. For isolated nuclear facilities, the data at periods of 1 s and 2 s must also be considered.

Table 1. Values of A_R for sites of nuclear facilities in the United States.

Period (s)	H_D	Site							
		North Anna	Summer	Vogtle	Oak Ridge	Hanford	Idaho	Los Alamos	Diablo Canyon
0.1	10^{-2}	9.8	8.2	8.3	6.7	4.2	2.9	6.0	4.7
	10^{-3}	5.6	3.6	3.3	4.5	3.2	2.4	4.2	2.7
	10^{-4}	3.4	2.9	2.8	2.8	2.3	2.1	2.5	-[1]
0.2	10^{-2}	7.2	7.3	7.6	5.5	3.9	2.8	5.7	4.7
	10^{-3}	5.0	3.3	3.1	4.1	3.1	2.3	4.3	2.7
	10^{-4}	3.4	2.8	2.5	2.9	2.3	2.0	2.6	1.9
1	10^{-2}	5.5	7.7	8.1	5.9	4.2	2.7	5.5	4.0
	10^{-3}	3.6	3.2	3.1	3.2	2.7	2.1	4.6	2.9
	10^{-4}	3.5	2.5	2.3	3.1	2.1	1.9	2.9	1.9
2	10^{-2}	6.5	9.3	9.8	7.6	5.5	3.1	5.8	4.0
	10^{-3}	3.3	3.3	3.2	3.1	3.0	2.5	4.6	2.8
	10^{-4}	3.2	2.5	2.4	2.8	2.0	2.0	2.9	2.0

[1] Information not available at the USGS website.

3.2. *Performance objectives*

The target frequency of unacceptable performance, P_F, for SDC 5 facilities (e.g., NPPs) is 1×10^{-5} for shaking with mean annual exceedance frequency, H_D, of 10^{-4}. A probability ratio, R_P, is defined as the ratio of the H_D and P_F:

$$R_P = \frac{H_D}{P_F} \tag{4}$$

The DF is derived considering uncertainties in seismic demand and deterministic component capacity, and expected component inelastic energy dissipation to achieve a target R_P (or a target P_F). It is given by (e.g., DOE (1994), ASCE (2005)):

$$DF = \frac{1}{F_{Np}} \left(R_P e^{-\left(X_P K_H \beta - \frac{1}{2} (K_H \beta)^2 \right)} \right)^{1/K_H} \tag{5}$$

where F_{Np} is the nominal frequency of unacceptable performance, K_H is a parameter to characterize the slope of the seismic hazard curve between two MAFEs[1] (wherein the slope is linear in the log-log space), β is a composite standard deviation associated with the mean seismic fragility curve, X_p is the standard normal variable corresponding to a failure probability, and other parameters were defined previously. The value of β typically ranges between 0.3 and 0.6 for nuclear structures and components. The parameter K_H in Eq. (5) and A_R in Eq. (2) are related by (ASCE, 2005)

$$K_H = \frac{1}{\log_{10}(A_R)} \tag{6}$$

where all parameters were defined previously. The DF given by Eq. (5) is approximated using Eq. (2), which is derived from a regression analysis between DF and A_R for different values of R_P and β (e.g., DOE (1994)).

The target performance goals specified in ASCE 43 can also be achieved if it is demonstrated that 1) the probability of unacceptable performance when subjected to the seismic hazard DRS is less than 1%, and 2) the probability of unacceptable performance when subjected to 1.5 times DRS is less than 10%. It is shown in the commentary to the ASCE 43 that the target performance goals are reasonably achieved if the above two criteria are satisfied and DF is given by Eq. (2).

4. Seismically isolated nuclear power plants

4.1. Seismic hazard definition

The draft USNRC technical report (NUREG/CR) entitled "Technical considerations for seismic isolation of nuclear facilities" (Kammerer *et al.*, forthcoming) identifies two levels of seismic hazard for design, namely, a ground motion response spectrum+ (GMRS+) and a beyond design basis (BDB) GMRS. The GMRS is calculated per Regulatory Guide RG 1.208 (USNRC, 2007a), "A performance-based approach to define the site-specific earthquake ground motion". This regulatory guide was developed to be used with performance criteria in ASCE 43 (ASCE, 2005), which was drafted for conventionally founded (fixed-base) nuclear structures. The GMRS is the product of the UHRS with an MAFE of 10^{-4} (SDC 5) and DF, and is similar to the DRS for a conventionally founded (non-isolated) nuclear structure. The GMRS+ is the envelope of the GMRS and a regulator-specific minimum response spectrum (e.g., an appropriate spectral shape anchored to a peak ground acceleration of 0.1 g). The BDB GMRS is the envelope of a UHRS with an MAFE of 10^{-5} and a spectrum with ordinates 167% of the GMRS+.

[1] A ten-fold ratio is considered (e.g., between MAFEs of 10^{-4} and 10^{-5}).

4.2. Performance objectives

The following performance goals are outlined in Kammerer *et al.* (forthcoming) for the isolated superstructure, individual isolators and umbilical lines: 1) the probability of the isolated superstructure striking the surrounding stop should be less than 1% for GMRS+ shaking, 2) the probability of the isolated superstructure striking the stop should be less than 10% for BDB GMRS shaking, 3) the probability of loss of axial load capacity of the isolators at a displacement equal to the clearance to the stop (CS) should be less than 10%, and 4) there should be a less than 10% probability of loss of function for safety-related umbilical lines at a displacement equal to the CS. These performance objectives are satisfied by providing the CS equal to or greater than the 90th percentile displacement for BDB GMRS shaking[2], and designing/testing the bearings and umbilical lines to perform with 90% confidence at a displacement equal to CS. The performance objectives are summarized in Table 2. The annual frequencies of unacceptable performance for the isolated superstructure, individual isolators and the umbilical lines are estimated later in this paper, assuming the objectives of Table 2 are achieved. Because the mean annual frequency of contact of the stop and the isolated superstructure is tiny, the review team assembled by the Lawrence Berkeley National Laboratory (see Acknowledgements) and the authors concluded that impact analysis of the isolated superstructure was unnecessary.

Table 2. Performance and design expectations for seismically isolated nuclear power plant structures[1] (adapted from Kammerer *et al.* (forthcoming)).

	Isolation system				
Ground motion levels	Isolator unit and system design and performance criteria	Approach to demonstrating acceptable performance of an isolator unit	Superstructure design and performance	Umbilical line design and performance	Moat or stop design and performance
GMRS+[3] Envelope of RG 1.208 GMRS and the minimum foundation input motion[2]	No long-term change in mechanical properties. Extremely high confidence of the isolation system surviving without damage when subjected to the mean displacement of the isolation system under the GMRS+ loading.	Perform production testing on each isolator for the mean system displacement under the GMRS+ loading and corresponding axial force.	Superstructure design and performance to conform to NUREG-0800 for GMRS+ loading.	Umbilical line design and performance to conform to NUREG-0800 for GMRS+ loading.	Moat gap sized such that there is less than 1% probability of the superstructure impacting the moat or stop for GMRS+ loading.
BDBE GMRS[4] Envelope of the UHRS at a MAFE of 1×10^{-5} and 167% of the GMRS+ (per ISG 20)	90% confidence of each isolator and the isolation system surviving without loss of gravity-load capacity at the mean displacement under BDBE GMRS loading.	Perform prototype testing on a sufficient number of isolators at the CS[5] displacement and the corresponding axial force for demonstrating acceptable performance with 90% confidence. Limited isolator unit damage is acceptable but load bearing capacity must be maintained.	Less than a 10% probability of the superstructure contacting the moat or stop under BDBE GMRS loading.	Greater than 90% confidence that each type of safety-related umbilical line, together with its connections, shall remain functional for the CS displacement. Performance may be demonstrated by testing, analysis or a combination of both.[6]	Moat gap sized such that there is less than a 10% probability of the superstructure impacting the moat or stop for BDB GMRS loading. Stop designed to arrest impact forces associated with isolation system displacement at 90th percentile BDBE isolation system displacement.[7] Limited damage to the moat or stop is acceptable but the moat/stop should [illegible].

1. Analysis and design of safety-related superstructures and systems shall conform to NUREG-0800.
2. 10CFR50 appendix S requires the use of an appropriate free-field spectrum (often the RG 1.60 spectral shape) with a peak ground acceleration of not less than 0.10g at the foundation level.
3. The analyses can be performed once using a composite spectrum or twice using the GMRS and the minimum spectrum separately.
4. The analyses can be performed once using a composite spectrum or twice using the 1×10^{-5} MAFE UHRS and 167% GMRS+ separately.
5. CS = clearance to the Stop.
6. Seismic Category I SSCs whose failure could impact the functionality of umbilical lines shall also remain functional for the CS displacement.
7. Impact velocity calculated at the clearance to the stop assuming system response of the isolation system for motions associated with the 90th percentile (or greater) BDB GMRS displacement.

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[2] The 90th percentile BDB GMRS displacement controls the clearance to the stop (e.g., Kumar et al. (2015)).

5. Spectral demands for conventional and isolated nuclear power plants

This section compares the definitions of seismic hazard for conventional and seismically isolated NPP structures, namely, 1) UHRS[3] at MAFE of 10^{-4}, 2) $1.67\times$UHRS at MAFE of 10^{-4}, 3) UHRS at MAFE of 10^{-5}, and 4) $DF\times$UHRS at MAFE of 10^{-4}, for the eight sites of Fig. 2 and 5% damping. Spectral acceleration at a MAFE is computed assuming a linear variation of spectral acceleration with MAFE between two adjacent data points on the seismic hazard curve in the logarithmic space. The first three hazard definitions are relevant for seismically isolated NPPs and the fourth, given by Eq. (1), forms the design basis for conventionally founded (non-isolated) NPPs. The DF is computed for SDC 5, which is appropriate for NPP structures, per Eq. (2) and is used to calculate the DRS for a conventionally founded (non-isolated) NPP. Table 3 presents the 5%-damped spectral acceleration ordinates for the four hazard levels at periods of 1 s and 2 s: periods relevant for isolated nuclear structures. The ordinates for $1.67\times$UHRS at MAFE of 10^{-4} are 1) greater than those of the DRS for conventionally founded nuclear structures, namely, $DF\times$UHRS at MAFE of 10^{-4}, and 2) always smaller than those of the UHRS at MAFE of 10^{-5}. The return periods corresponding to the spectral accelerations are listed in Table 4.

Table 3. Five percent damped spectral ordinates (in g) at 1 s and 2 s for seismic hazards defined for conventionally founded and seismically isolated nuclear power plants at eight sites of nuclear facilities.

Period (s)	Hazard definition	Site							
		North Anna	Summer	Vogtle	Oak Ridge	Hanford	Idaho	Los Alamos	Diablo Canyon
1	UHRS1[1]	0.12	0.22	0.20	0.21	0.25	0.14	0.36	0.83
	UHRS2[2]	0.41	0.54	0.47	0.64	0.53	0.27	1.06	1.59
	1.67×UHRS1	0.19	0.36	0.34	0.35	0.42	0.23	0.60	1.39
	DF×UHRS1	0.19	0.27	0.24	0.31	0.27	0.14	0.51	0.84
2	UHRS1	0.06	0.12	0.11	0.11	0.14	0.09	0.15	0.38
	UHRS2	0.19	0.29	0.26	0.31	0.29	0.18	0.44	0.75
	1.67×UHRS1	0.10	0.19	0.18	0.19	0.24	0.15	0.25	0.64
	DF×UHRS1	0.09	0.15	0.13	0.15	0.15	0.09	0.21	0.39

[1]UHRS with an MAFE of 10^{-4}
[2]UHRS with an MAFE of 10^{-5}

6. Annual frequency of unacceptable performance of isolated nuclear power plants designed per the forthcoming NUREG/CR

6.1. Hazard definition

The seismic hazard is defined, for the purpose of estimating the annual frequency of unacceptable performance, as multiples, m, of UHRS shaking at MAFE of 10^{-4}, taken as the average of the multiples of the spectral acceleration ordinates at 1 s and 2 s[4, 5] reported in Fig. 1.

[3] It is demonstrated later in the paper that *DF* can be set equal to 1.0 for seismically isolated NPPs.
[4] The periods of 1 s and 2 s are relevant for seismically isolated structures, as noted previously.
[5] The amplification ratios for 1 s and 2 s and at MAFE of 10^{-4} differ by less than 10% for the eight sites of Fig. 2.

This definition does not include the DF recommended by RG 1.208 and ASCE 43 at the MAFE of 10^{-4} (see Section 3.1) for the reason discussed later. The seismic hazard curves considered for eight NPP sites of Fig. 2 are plotted in Fig. 3.

Table 4. Return periods corresponding to the 5% damped spectral accelerations at 1 s and 2 s reported in (in 1000s of years).

Period (s)	Hazard definition	Site							
		North Anna	Summer	Vogtle	Oak Ridge	Hanford	Idaho	Los Alamos	Diablo Canyon
1	UHRS1[1]	10	10	10	10	10	10	10	10
	UHRS2[2]	100	100	100	100	100	100	100	100
	1.67×UHRS1	25	35	39	28	46	61	26	59
	DF×UHRS1	24	17	15	21	13	10	19	10
2	UHRS1	10	10	10	10	10	10	10	10
	UHRS2	100	100	100	100	100	100	100	100
	1.67×UHRS1	28	34	36	31	48	48	26	54
	DF×UHRS1	24	17	16	20	12	12	19	11

[1]UHRS with an MAFE of 10^{-4}
[2]UHRS with an MAFE of 10^{-5}

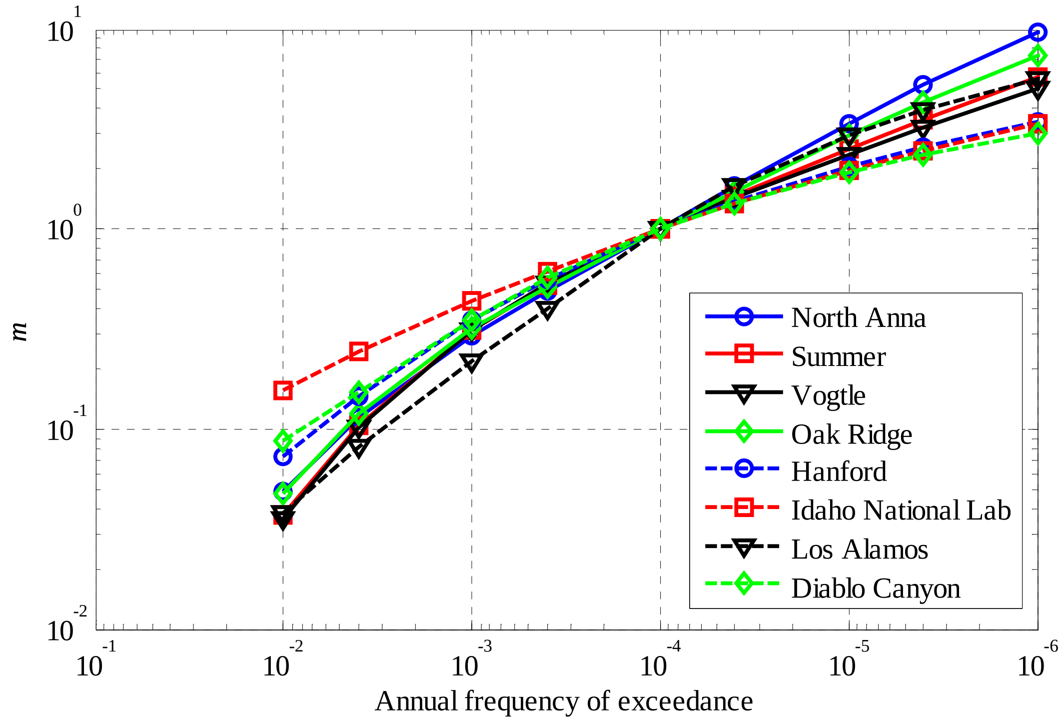


Fig. 3. Annual frequency of exceedance of multiples, m, of UHRS with MAFE of 10^{-4}

6.2. Annual frequency of unacceptable performance of the isolated superstructure

The superstructure of a seismically isolated NPP will include structural components that will be designed in accordance with materials standards such as ACI 349 (ACI, 2013a), ACI 359 (ACI, 2013b) and AISC N690 (AISC, 2012) and safety-related mechanical and electrical systems and components designed or qualified in accordance with standards prepared by the American Society of Mechanical Engineers (ASME) and the Institute of Electrical and Electronics Engineers (IEEE). These structural, mechanical and electrical components must be designed, per materials standards, for the forces, displacements and accelerations associated with GMRS+ shaking per Table 2, as a minimum.

Seismic isolation of NPPs that already have a design certification has been proposed as a viable strategy to expand the use of existing designs, noting some of the plants have been seismically qualified for horizontal design basis shaking that is represented by a USNRC RG 1.60 (USAEC (1973), USNRC (2014)) spectrum anchored to peak ground acceleration of 0.3 g. For this spectrum and peak acceleration, and assuming that the period of the fixed-base superstructure is in the range of 0.1 s to 0.3 s, the horizontal spectral response at 5% damping will be no less than 0.75 g, which might form the design basis for some of the structural components. The mechanical and electrical safety-related systems and components would be typically designed, per ASME and IEEE standards, for floor spectral demands much in excess of 1.0 g. If the annual frequency of unacceptable performance of structures, systems and components in a (fixed-base) certified plant design meets the requirements of USNRC, there will exist a considerable margin if the certified plant is seismically isolated. Noting that the focus to date has been on response to horizontal shaking, the response to vertical shaking will be no better and no worse if the superstructure is isolated using either sliding or elastomeric bearings. In summary, the isolation of a certified plant design will reduce the annual frequency of unacceptable performance of the superstructure below the currently calculated value.

Huang *et al.* (2010) showed that the required seismic capacity of structures, systems and components (SSCs) in NPPs could be substantially reduced if the plant was seismically isolated. The associated reduction in cost of the SSCs could substantially offset (or eliminate) the costs associated with the seismic isolators, pedestals, foundation and associated excavation (if the plant is embedded). If reductions in demands are incorporated into a design, the owner/operator of the site-specific NPP would have to demonstrate, through plant-level risk assessments, that the resultant SSC designs meet USNRC-required performance goals. Herein, it is assumed that the annual frequency of unacceptable performance of the isolated superstructure, system and components is less than that of the corresponding fixed-base NPP.

One requirement of the forthcoming seismic isolation NUREG/CR is that there be a less than 10% probability of the superstructure impacting the moat or stop under BDB GMRS shaking. This deterministic objective is met by setting the clearance to the stop, along each horizontal axis of the plant, to be no less than the 90^{th} percentile displacement calculated for BDB GMRS shaking along that axis. Analysis of the isolated superstructure for impact loadings associated with collision with the stop is not required if this clearance to the stop is provided.

6.3. Annual frequency of unacceptable performance of the isolation system

In the seismic domain, the isolation system represents a singleton: failure of the isolation system could correspond to unacceptable performance of the nuclear plant in terms of core damage or large release of radiation. It is not possible to generically relate the failure of individual isolators to the failure of an isolation system. The failure of one isolator in a system of four could trigger system failure. The failure of one isolator in a system of 250 would be inconsequential. Herein, and very conservatively, the failure of one isolator is assumed to represent the failure of the isolation system.

To compute the annual frequency of unacceptable performance of an isolator unit, an isolator-unit fragility function must be convolved over an appropriate seismic hazard curve. The hazard curves assumed here for the eight sites of Fig. 2 are based on the averaged values, site by site, for periods of 1.0 s and 2.0 s. The fragility function for an isolator unit is defined by a median, θ, and log standard deviation, β, as follows

$$\theta - X_p \beta = \log_e(m) \tag{7}$$

where X_p corresponds to a probability of exceedance of p for a normally distributed data set, and other parameters were defined previously. If tight quality control on isolator production is maintained, the variability in the properties of isolator units of a given size will be small. The values of β considered here is 0.05 (results for β of 0.01 and 0.02 are presented in Kumar et al. (2015)). If a stop is constructed, the probability of isolator failure at calculated displacements equal to or greater than the clearance to the stop (CS) is equal to that at the stop[6]. Two calculations of the annual frequency of isolator failure are presented below, one assumes that no stop is present and the other assumes the stop is installed at the 90+$^{\text{th}}$ percentile BDB GMRS displacement.

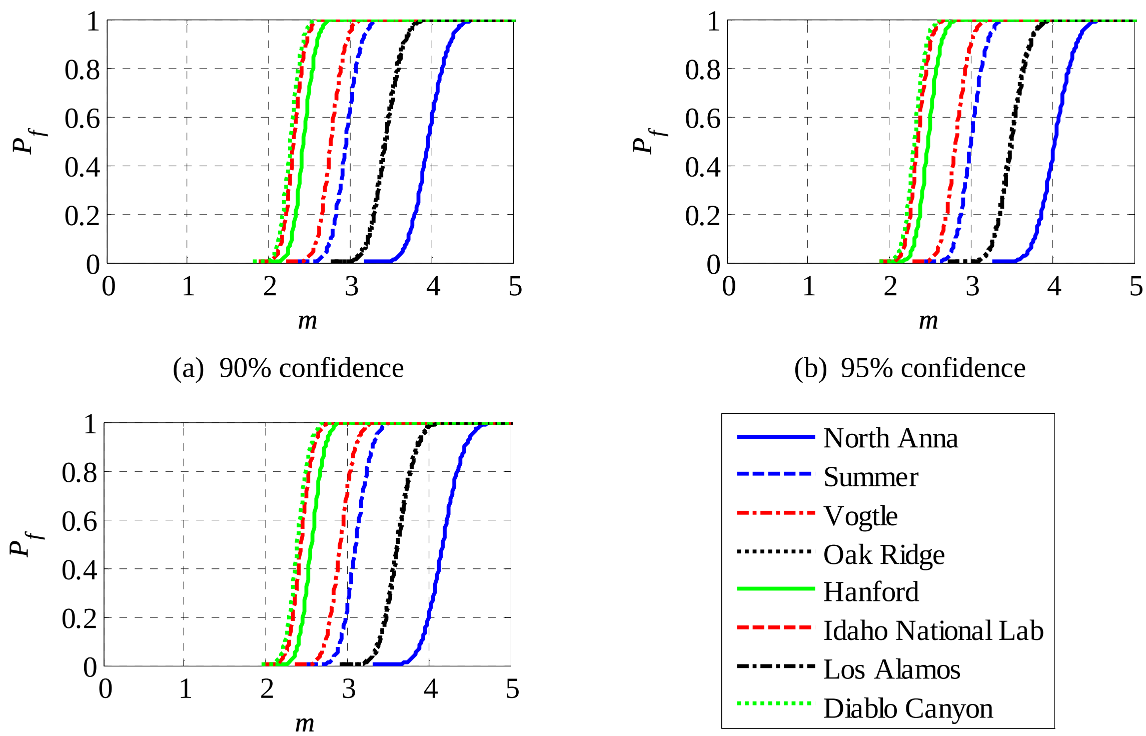
As noted in Section 4.2, isolators are ***prototype*** tested to ensure that they can sustain the 90$^{\text{th}}$ percentile BDB GMRS displacement and the co-existing axial force with 90+% confidence. Practically, this requires all of the prototype isolators to resist this combination of displacement and axial force unless very large numbers of prototypes are to be tested (to achieve the 90+% confidence). Likely a small number of ***prototype*** isolators will be tested to greater displacements and forces to demonstrate compliance. Assume that the displacement capacity of the isolation system is equal to the 90$^{\text{th}}$ percentile displacement for BDB GMRS shaking, which is approximately equal to the median displacement for 110% BDB GMRS[7] shaking, as shown in Kumar et al. (2015). Based on this assumption, and values of 90% (1 isolator in 10 fails), 95% (1 isolator in 20 fails) and 99% (1 isolator in 100 fails) confidence, Eq. (7) is rewritten as:

$$\theta - \alpha\beta = \log_e\left(f_{AR} \times \bar{A}_R\right) \tag{8}$$

[6] Penetration of the isolated superstructure into the stop is assumed to be negligible.

[7] These calculations are performed in Kumar et al. (2015) for three sites, namely, Diablo Canyon, Vogtle and North Anna, to cover the range of A_R at H_D of 10^{-4} for 1 s and 2 s, and the eight sites of Fig. 2 (see Table 1). One hundred and ten percent is appropriate for Diablo Canyon and conservative (low) for the other eight sites.

where α is 1.28, 1.64, and 2.33, respectively, and f_{AR} is 1.10. The fragility curves for isolators tested with 90%, 95% and 99% confidence at median displacement for 110% BDB GMRS shaking (or 90th percentile displacement for BDB GMRS shaking) are shown in Fig. 4. Fig. 5 presents fragility curves for 90% confidence at median displacement for 125% BDB GMRS shaking $\left(f_{AR} = 1.25\right)$.



(a) 90% confidence

(b) 95% confidence

(c) 99% confidence

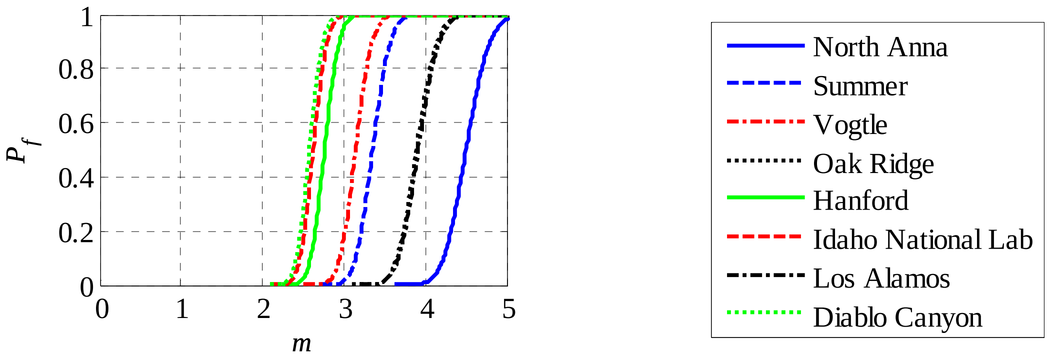
(d) Legend

Fig. 4. Probability of unacceptable performance, P_f, of individual isolator units tested at median displacement for 110% BDB GMRS shaking plotted against multiples, m, of UHRS shaking with MAFE of 10^{-4}, without a stop.

The total annual frequency of unacceptable performance of the isolation system, $P_{F,\text{isolation}}$, is given by (e.g., ASCE (2005)):

$$P_{F,\text{isolation}} = -\int_0^\infty \frac{d}{dm} H_D \times \left(P_f \mid GM = m\right) dm \tag{9}$$

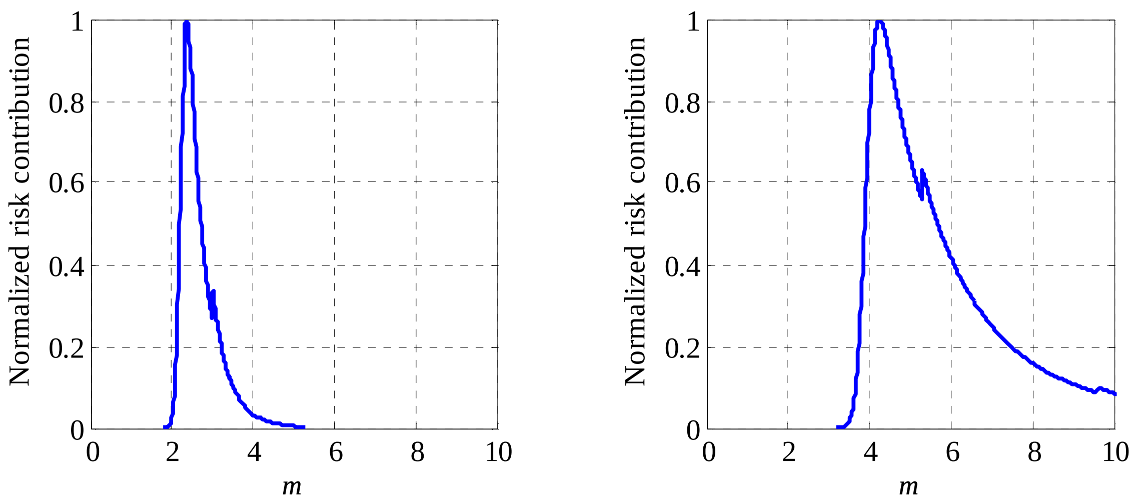
where $\left(P_f \mid GM = m\right)$ is the annual frequency of unacceptable performance conditioned on m times UHRS shaking at an MAFE of 10^{-4}, and other parameters were defined previously. The seismic risk at a site can be disaggregated as shown in Fig. 6 for the Diablo Canyon and North Anna sites corresponding to the fragility curves plotted in Fig. 4(a). The disaggregated risk peaks at m of 2.37 and 4.25 for the two sites, respectively, which correspond to 1.22 and 1.26 times the BDB GMRS shaking at the Diablo Canyon and North Anna sites, respectively. Shifting the peaks to greater values of m would reduce total risk, because the disaggregated risk for a given range of m would correspond to a smaller H_D. This shift can be achieved by either testing the bearings with a greater confidence (e.g., Fig. 4(c)) or testing them for greater displacements and axial forces, i.e., greater shaking intensity (e.g., Fig. 5).



(a) 90% confidence (b) Legend

Fig. 5. Probability of unacceptable performance, P_f, of individual isolator units for 90% confidence at median displacement for 125% BDB GMRS shaking plotted against multiples, m, of UHRS shaking with MAFE of 10^{-4}, without a stop.

The annual frequencies of exceedance for the eight sites of Fig. 2 are presented in Tables 5 and 6 corresponding to the fragility curves of Figs. 4 and 5, respectively. The frequencies are less than 1×10^{-5}, but greater than 1×10^{-6}, for all combinations of site, confidence level of testing, and displacement at which tests are performed. As expected, the annual frequency of unacceptable performance of the isolation system decreases if the bearings are tested with a greater confidence at a given displacement.



(a) Diablo Canyon (b) North Anna

Fig. 6. Disaggregation of risk for individual isolators.

Consider Tables 5 and 6, 90% confidence on isolator performance, and the sites of Los Alamos and Diablo Canyon. Increasing the displacement for prototype isolator testing from median displacement for 110% BDB GMRS shaking to median displacement for 125% BDB GMRS shaking reduces the annual frequency of unacceptable performance by 34% and 49% for the two sites, respectively. The percentage reduction is smaller for North Anna because a significant fraction of the risk accrues at large values of m (see Fig. 6).

Table 5. Annual frequency of unacceptable performance ($\times 10^{-6}$) of individual isolator units tested at median displacement for 110% BDB GMRS shaking, without a stop.

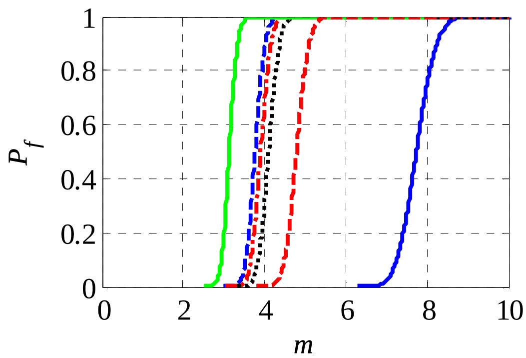
	Site							
Confidence	North Anna	Summer	Vogtle	Oak Ridge	Hanford	Idaho	Los Alamos	Diablo Canyon
90%	7.3	6.6	6.3	6.9	5.3	5.4	6.2	4.7
95%	7.0	6.3	5.9	6.6	5.0	5.0	5.8	4.3
99%	6.5	5.7	5.3	6.1	4.3	4.3	5.2	3.6

Table 6. Annual frequency of unacceptable performance ($\times 10^{-6}$) of individual isolator units tested at median displacement for 125% BDB GMRS shaking, without a stop.

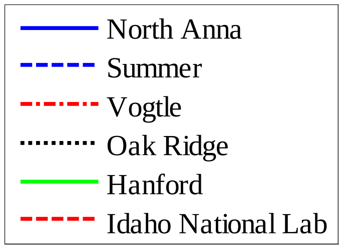
	Site							
Confidence	North Anna	Summer	Vogtle	Oak Ridge	Hanford	Idaho	Los Alamos	Diablo Canyon
90%	5.6	4.7	4.3	5.1	3.1	3.1	4.1	2.4

Importantly, the annual frequency of unacceptable performance for the isolation system will be much smaller than the values presented in Tables 5 and 6, because 1) failure of a small fraction of the isolators in an isolation system will not compromise the performance of the isolation system, and 2) the displacement and force demands on the isolators will not be fully correlated. Prototype isolators will be tested by type, for maximum and not average, compressive and tensile axial forces, and horizontal displacements. Although isolator horizontal displacements may be strongly correlated if in-plane torsion is very small, axial loads will be weakly correlated due to differences in gravity load, vertical shaking effects, and horizontal shaking-induced overturning moments.

The peak isolator displacement will vary as a function of the mechanical properties of the isolation system and site. To enable a comparison of horizontal displacement demands at the eight sites, the 100,000-year spectral demands at a period of 2 s and 5% damping presented in Table 3 are considered. The spectral displacement at six of the eight sites of Fig. 2, namely, the North Anna, Summer, Vogtle, Oak Ridge, Hanford and Idaho sites are less than one half that at the Diablo Canyon site. Increasing the displacement capacity of the isolation system at any of the six sites to one half of the 90th percentile displacement for BDB GMRS shaking at the Diablo Canyon site and testing the isolator units at this displacement will reduce the risk of unacceptable performance without increasing the cost of the isolation system considerably. The corresponding isolator fragility curve can be derived approximately by increasing the factor f_{AR} in Eq. (8) by the ratio, κ, of one half the 100,000-year 2 s spectral acceleration for the Diablo Canyon site to the 100,000-year 2 s spectral acceleration at the site. The ratio κ ranges between 1.2 and 2.1 for the six sites. The fragility functions for the isolator units tested with 90% confidence at a displacement (and corresponding axial force) equal to half the 90th percentile displacement for BDB GMRS shaking at the Diablo Canyon site are shown in Fig. 7 and the annual frequencies of unacceptable performance are listed in Table 7. These frequencies are smaller than the corresponding values reported in Table 5 by a factor of between 2 and 35.



(a) 90% confidence



(b) Legend

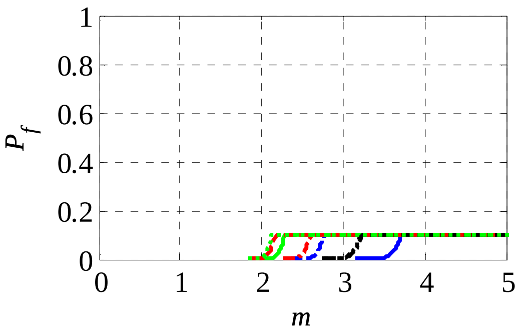
Fig. 7. Probability of unacceptable performance, P_f, of the individual isolator units tested with 90% confidence for median displacement for 110% κ BDB GMRS shaking plotted against multiples, m, of UHRS shaking with MAFE of 10^{-4}, without a stop.

Table 7. Annual frequency of unacceptable performance ($\times 10^{-6}$) of individual isolator units tested for median displacement for 110% κ BDB GMRS shaking, without a stop.

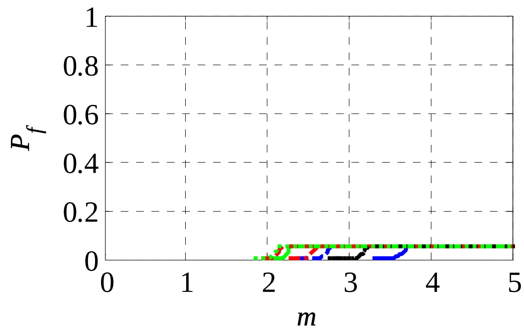
	Site					
Confidence	North Anna	Summer	Vogtle	Oak Ridge	Hanford	Idaho
90%	1.7	3.4	2.2	4.5	1.7	0.2

The above calculations were performed assuming no stop was present. If a stop is constructed at the median displacement for 110% BDB GMRS shaking (Fig. 4) or 125% BDB GMRS shaking (Fig. 5), the fragility curves will be truncated as shown in Figs. 8 and 9 for the two shaking levels, respectively. The corresponding annual frequencies of unacceptable performance of individual isolator units are listed in Tables 8 and 9, respectively. These frequencies are smaller than 10^{-6} for all combinations of site, confidence level on isolator and displacement at which isolators are tested. The frequencies decrease substantially with greater confidence in an isolator's performance.

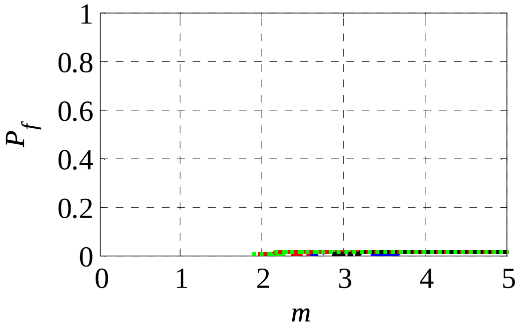
Providing a stop (and thus limiting the horizontal displacement of the isolators) at the six sites of Fig. 7 at the displacement equal to one half that required at the Diablo Canyon site would reduce the annual frequency of unacceptable performance. The fragility curves corresponding to $f_{AR} = 1.1\kappa$ are plotted in Fig. 10 and the annual frequencies of unacceptable performance are listed in Table 10. These frequencies are smaller than those of corresponding values reported in Table 8 by a factor of between 2 and 40.



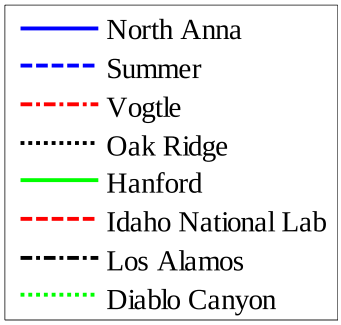
(a) 90% confidence



(b) 95% confidence

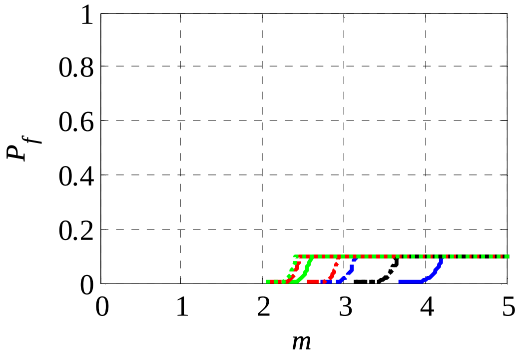


(c) 99% confidence

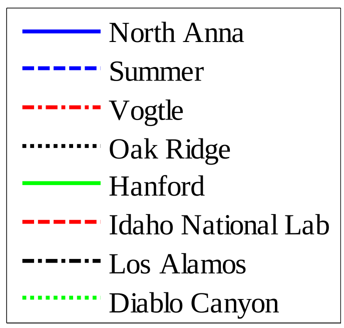


(d) Legend

Fig. 8. Probability of unacceptable performance, P_f, of individual isolator units tested at median displacement for 110% BDB GMRS shaking plotted against multiples, m, of UHRS shaking with MAFE of 10^{-4}, with a stop at median displacement for 110% BDB GMRS shaking.



(a) 90% confidence



(b) Legend

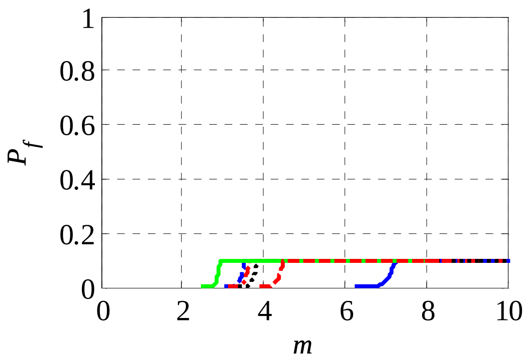
Fig. 9. Probability of unacceptable performance, P_f, of individual isolator units for 90% confidence at median displacement for 125% BDB GMRS shaking plotted against multiples, m, of UHRS shaking with MAFE of 10^{-4}, with a stop at median displacement for 125% BDB GMRS shaking.

Table 8. Annual frequency of unacceptable performance ($\times 10^{-6}$) of individual isolator units tested at median displacement for 110% BDB GMRS shaking, with a stop at median displacement for 110% BDB GMRS shaking.

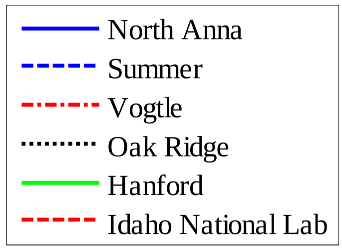
	Site							
Confidence	North Anna	Summer	Vogtle	Oak Ridge	Hanford	Idaho	Los Alamos	Diablo Canyon
90%	0.9	0.8	0.8	0.8	0.8	0.8	0.8	0.7
95%	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3
99%	0.09	0.08	0.08	0.08	0.07	0.07	0.08	0.07

Table 9. Annual frequency of unacceptable performance ($\times 10^{-6}$) of individual isolator units tested at median displacement for 125% BDB GMRS shaking, with a stop at median displacement for 125% BDB GMRS shaking.

	Site							
Confidence	North Anna	Summer	Vogtle	Oak Ridge	Hanford	Idaho	Los Alamos	Diablo Canyon
90%	0.7	0.6	0.5	0.6	0.4	0.4	0.5	0.4



(a) 90% confidence



(b) Legend

Fig. 10. Probability of unacceptable performance, P_f, of the individual isolator units tested with 90% confidence for median displacement for 110% κ BDB GMRS shaking plotted against multiples, m, of UHRS shaking with MAFE of 10^{-4}, with a stop at median displacement for 110% κ BDB GMRS shaking.

Table 10. Annual frequency of unacceptable performance ($\times 10^{-6}$) of individual isolator units tested for median displacement for 110% κ BDB GMRS shaking, with a stop at median displacement for 110% κ BDB GMRS shaking.

	Site					
Confidence	North Anna	Summer	Vogtle	Oak Ridge	Hanford	Idaho
90%	0.2	0.4	0.3	0.6	0.3	0.02

6.4. Annual frequency of unacceptable performance of safety-related umbilical lines

The performance expectations for safety-related umbilical lines that cross the isolation interface are identical to those for the seismic isolators because both serve a critical safety function. Umbilical lines may be qualified by analysis, testing, or a combination of both.

The annual frequency of unacceptable performance of safety-related umbilical lines is calculated using an approach similar to that for the isolation system presented in Section 6.3. Failure of each safety-related umbilical line is very conservatively assumed to result in core damage and release of radiation, because mitigating measures are ignored, noting they will vary as a function of plant design. The fragility curves of the umbilical lines tested with different confidence and shaking level combinations are considered identical to those for individual isolator units, with or without a stop. The resulting annual frequencies of unacceptable performance are less than 1×10^{-5} and 1×10^{-6} without and with a stop, respectively.

7. Annual frequency of unacceptable performance of isolated nuclear power plants designed per ASCE Standard 4

7.1. ASCE Standard 4 for isolated nuclear structures

The United States DOE uses ASCE Standard 4 and ASCE Standard 43 for seismic analysis and design of safety-related nuclear structures. A new DOE-regulated NPP would likely be assigned to SDC 5, for which ASCE 43 specifies the hazard exceedance frequency for the design earthquake to be 10^{-4} and the target performance goal to be 1×10^{-5}.

Section 1.3 of ASCE 43 writes that the target performance can be achieved by satisfying two criteria, namely, 1) less than about a 1% probability of unacceptable performance for the design basis earthquake (DBE) ground motion, and 2) less than about a 10% probability of unacceptable performance for a ground motion equal to 150% of the DBE ground motion. In ASCE 43, the DBE ground motion is defined in terms of a design response spectrum with ordinates equal to the product of the UHRS at the specified MAFE and DF. For an NPP, the UHRS is specified at an MAFE of 1×10^{-4}.

ASCE Standard 4 includes a chapter on seismic isolation. The target performance goal of 1×10^{-5} for a seismically isolated SDC 5 safety-related nuclear structure is achieved using the two criteria listed above, where unacceptable performance of the isolation system is conservatively measured in terms of insufficient capacity of individual isolators, identical to Section 6. Herein, DF is assumed to be 1.0, which is confirmed through risk calculations.

The following sections present fragility curves and the calculation of annual frequency of unacceptable performance based on isolators being designed and tested per the provisions of the ASCE Standard 4, namely, there be 90+% confidence that the isolators can support axial loads at a horizontal displacement equal to the clearance to the stop, CS, where CS is no less than the 90th percentile horizontal displacement for 150% DBE shaking. The risk calculations performed in Section 6.2 are repeated for isolators tested with 90% confidence at 90th percentile horizontal displacement for 200% DBE shaking. The *median* fragility curves are developed assuming that the 90th percentile displacement for 150% (200%) DBE shaking is equal to the median displacement at 1.1 times 150% (200%) DBE shaking (see Kumar et al. (2015)). The hazard curves plotted in Fig. 3 are used for the risk calculations.

7.2. Isolators tested at 90th percentile displacement for 150% DBE shaking

Fig. 11 presents fragility curves for isolators tested with 90%, 95% and 99% confidence at median displacement for 165% DBE shaking (or 90th percentile displacement for 150% DBE shaking) with no stop. The annual frequencies of unacceptable performance for isolators with fragility curves of Fig. 11 are listed in Table 11. A small reduction in risk is achieved if the confidence level on isolator performance is increased from 90% to 99%. The annual frequencies of unacceptable performance reported in Table 11 are greater than 1×10^{-5} for all combinations considered here: a stop is most likely needed in isolated SDC 5 nuclear structures to achieve the target performance goal.

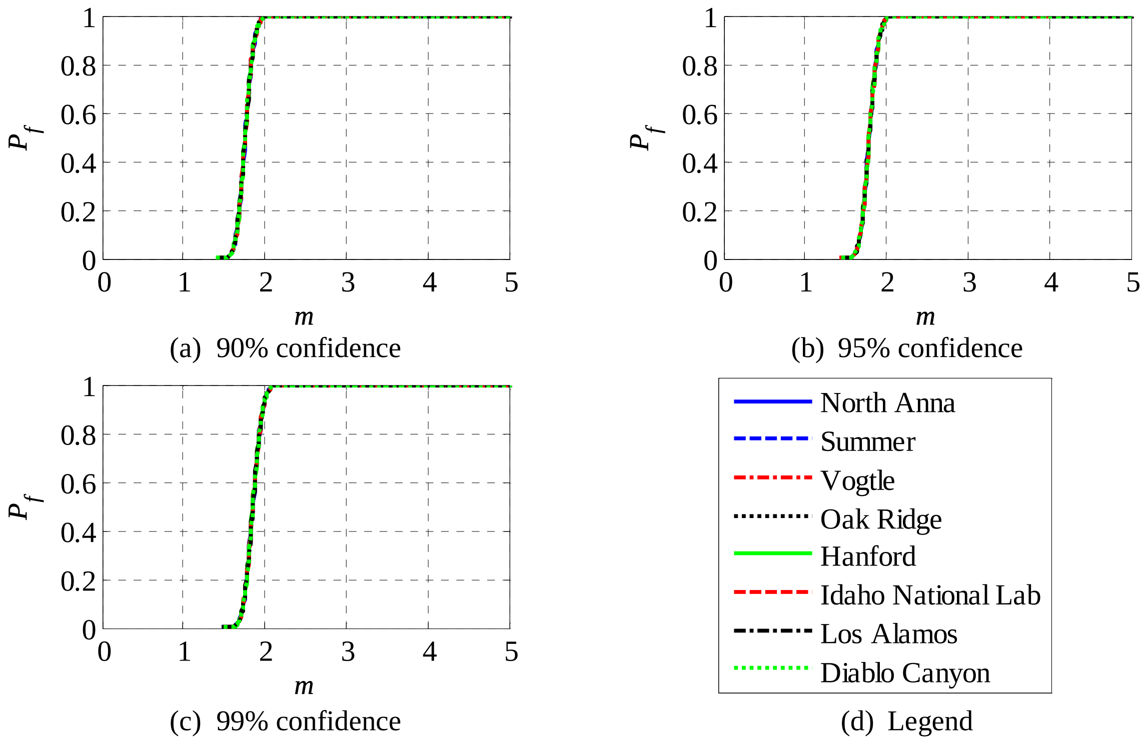


Fig. 11. Probability of unacceptable performance, P_f, of individual isolator units for 90% confidence at median displacement for 165% DBE shaking plotted against multiples, m, of UHRS shaking with MAFE of 10^{-4}, without a stop.

The above calculations were performed assuming no stop was present. The fragility curves of Fig. 11 are truncated at the specified level of confidence to acknowledge the presence of a stop, as shown in Fig. 12. The annual frequencies of unacceptable performance for the stop-enabled fragility curves are listed in Table 12. All of the listed frequencies are considerably smaller than the target performance goal of 1×10^{-5} for all combinations of site, confidence, and test displacement, indicating that a value of DF equal to 1.0 is appropriate for seismically isolated

SDC 5 nuclear structures, provided the effects of vertical shaking do not control the design. In contrast to the results without a stop, when a stop is present, the risk is reduced substantially if the confidence on isolator performance is increased from 90% to 99%.

Table 11. Annual frequency of unacceptable performance ($\times 10^{-6}$) of individual isolator units tested at median displacement for 165% DBE shaking, without a stop.

	Site							
Confidence	North Anna	Summer	Vogtle	Oak Ridge	Hanford	Idaho	Los Alamos	Diablo Canyon
90%	34.8	25.2	22.8	30.5	17.9	15.2	34.3	14.7
95%	33.5	24.2	21.7	29.4	16.8	14.2	33.0	13.7
99%	31.4	22.0	19.8	27.2	15.0	12.6	30.3	12.0

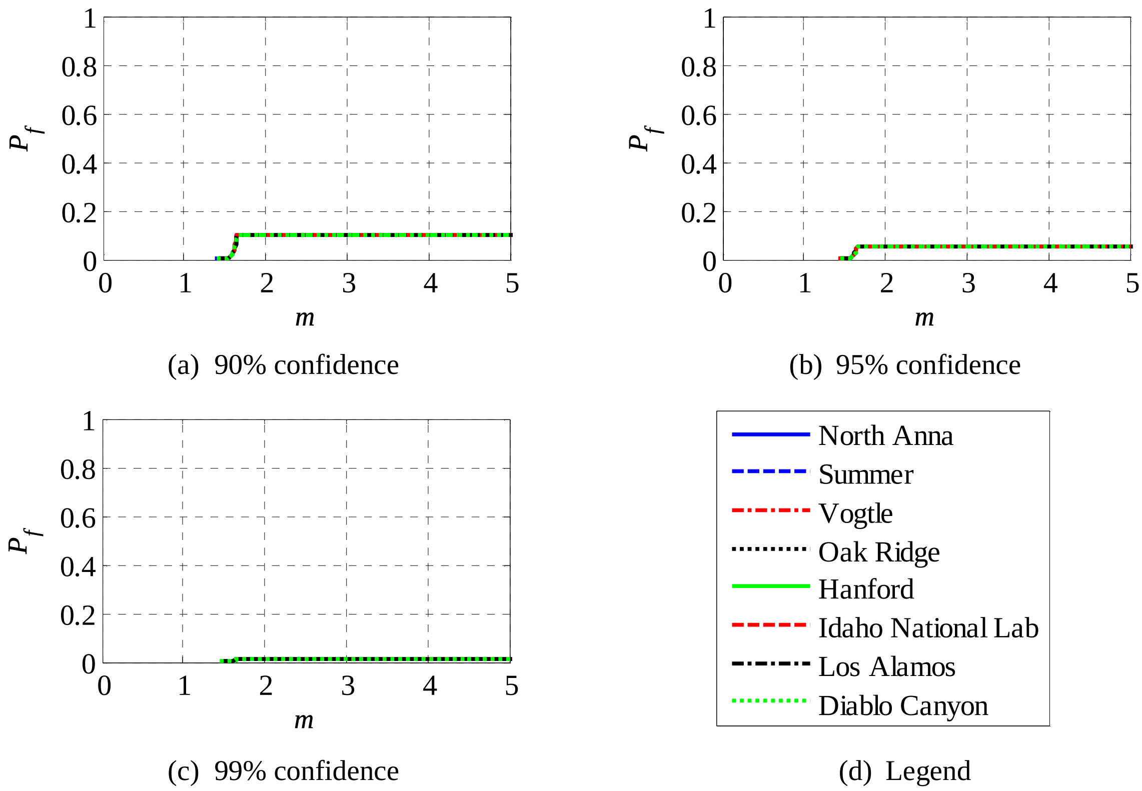


Fig. 12. Probability of unacceptable performance, P_f, of individual isolator units tested at median displacement for 165% DBE shaking plotted against multiples, *m*, of UHRS shaking with MAFE of 10^{-4}, with a stop at median displacement for 165% DBE shaking.

7.3. Isolators tested at 90th percentile displacement for 200% DBE shaking

The 2 s seismic demand at the Diablo Canyon site is more than twice the demand at the other sites considered in this study, with the exception of the Los Alamos site (see Table 3). Isolators with capacity just sufficient for Diablo Canyon would have excess capacity at all other sites, leading to the question, “By how much is risk reduced if the beyond design basis shaking is assumed to be twice the design basis shaking?” This question is addressed below.

Table 12. Annual frequency of unacceptable performance ($\times 10^{-6}$) of individual isolator units tested at median displacement for 165% DBE shaking, with a stop at median displacement for 165% DBE shaking.

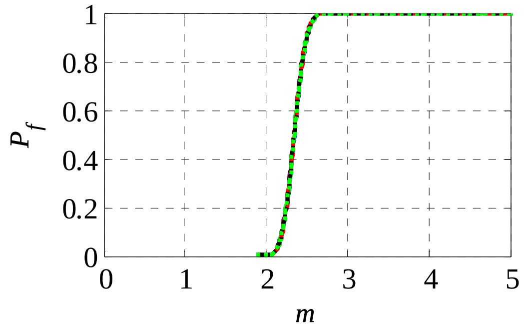
	Site							
Confidence	North Anna	Summer	Vogtle	Oak Ridge	Hanford	Idaho	Los Alamos	Diablo Canyon
90%	4.1	3.1	2.9	3.7	2.4	2.1	4.2	2.0
95%	2.0	1.6	1.4	1.8	1.2	1.0	2.1	1.0
99%	0.4	0.3	0.3	0.4	0.2	0.2	0.4	0.2

The fragility curves of Figs. 11 and 12 are re-generated for isolators tested with 90%, 95% and 99% confidence at median displacement for 220% (= 1.1 times 200%: converting 90th percentile displacements to median displacements, as described previously) DBE shaking, and are plotted in Figs. 13 and 14, respectively. The corresponding annual frequencies of unacceptable performance are listed in Tables 13 and 14, respectively. The frequencies are greater than 1×10^{-5} for five of the eight sites if a stop is not provided and considerably less than 1×10^{-5} for all eight sites if a stop is provided. (The risk numbers in the last column of Table 13 are similar to those in the corresponding column of Table 5, because 2.0 times DBE shaking for Diablo Canyon is approximately equal to shaking with an MAFE of 1×10^{-5}: the seismic isolation NUREG/CR definition of beyond design basis shaking.)

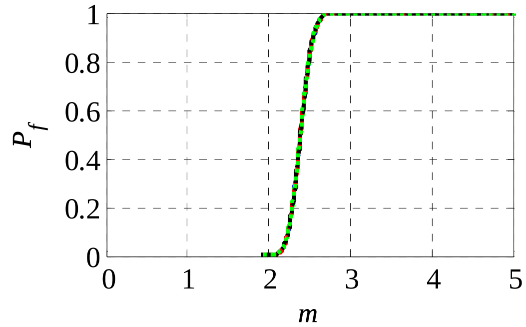
The increase in shaking intensity from 150% DBE to 200% DBE for the purpose of establishing displacements for testing isolators leads to a significant reduction in risk, with the greatest reductions for the sites of highest seismic hazard (e.g., the Diablo Canyon site, a factor of between 3.5 and 4) and the smallest reductions for the sites of lowest seismic hazard (e.g., the North Anna site, a factor of approximately 1.7). The significant difference in the slope on the seismic hazard curves for sites of low and high seismicity is the reason why the risk reductions are not uniform for a consistent increase in the shaking intensity from 150% DBE to 200% DBE. However, the annual frequency of unacceptable performance is greater than the target performance goal of 1×10^{-5} for five of the eight sites. A stop would still be needed for these five sites if 200% DBE shaking rather than 150% DBE shaking is used to define beyond design basis shaking. There is no practical risk-based benefit to increasing the shaking intensity used to define beyond design basis shaking.

8. Design factor for seismically isolated nuclear power plants

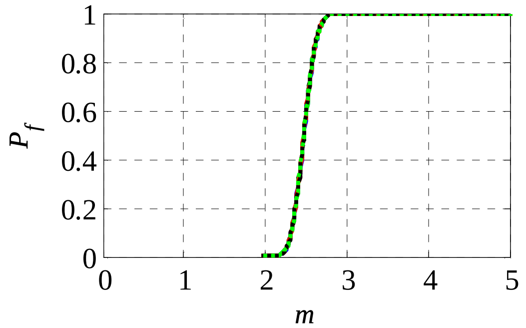
The target annual frequency of unacceptable performance for a structure, system or component in a conventionally founded NPP (SDC 5 per ASCE 43) is 10^{-5}. This goal is achieved by using materials standards such as ACI 349 and seismic demands consistent with a GMRS calculated as the product of a UHRS at an annual frequency of exceedance of 10^{-4} and a DF of 1.0 or greater.



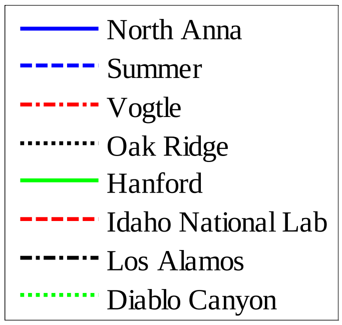
(a) 90% confidence



(b) 95% confidence



(c) 99% confidence



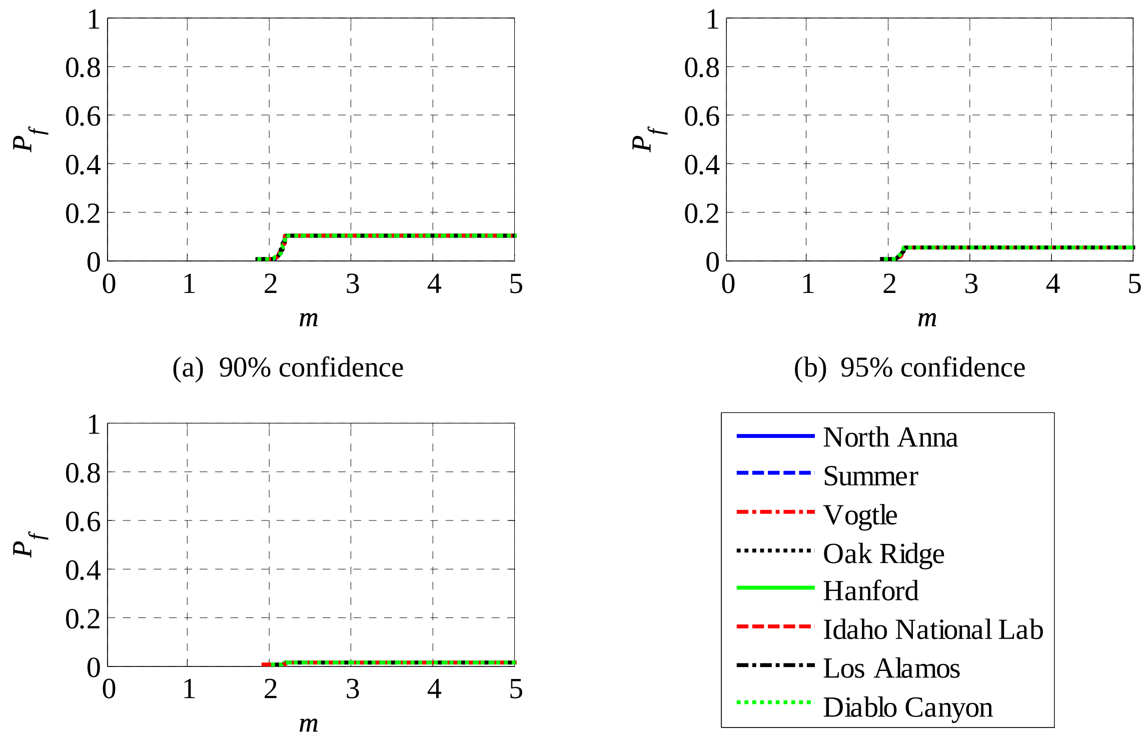
(d) Legend

Fig. 13. Probability of unacceptable performance, P_f, of individual isolator units for 90% confidence at median displacement for 220% DBE shaking plotted against multiples, *m*, of UHRS shaking with MAFE of 10^{-4}, without a stop.

Table 13. Annual frequency of unacceptable performance ($\times 10^{-6}$) of individual isolator units tested at median displacement for 220% DBE shaking, without a stop.

	Site							
Confidence	North Anna	Summer	Vogtle	Oak Ridge	Hanford	Idaho	Los Alamos	Diablo Canyon
90%	20.1	12.1	10.2	16.3	6.2	5.0	17.3	4.0
95%	19.4	11.5	9.7	15.7	5.8	4.7	16.5	3.6
99%	18.2	10.5	8.8	14.5	5.0	4.1	15.2	3.0

The calculations presented in Section 6 (7) were based on a GMRS (DRS) calculated using a UHRS at an annual frequency of exceedance of 10^{-4} and *DF* equal to 1.0, and a BDB GMRS that is defined, for the sites considered here, by a UHRS at an annual frequency of exceedance of 10^{-5} (150% DRS or 200% DRS). These calculations show that the annual frequency of unacceptable performance is greater than 1×10^{-6} (greater than 1×10^{-5}) if the isolation system is designed per the forthcoming NUREG/CR (ASCE 4) and no stop is provided, and less than 1×10^{-6} (less than 1×10^{-5}) if a stop is installed at the 90th percentile BDB GMRS (150% DRS) displacement, confirming that *DF* can be set equal to 1.0 for seismically isolated NPPs.



(a) 90% confidence (b) 95% confidence

(c) 99% confidence (d) Legend

Fig. 14. Probability of unacceptable performance, P_f, of individual isolator units tested at median displacement for 220% DBE shaking plotted against multiples, *m*, of UHRS shaking with MAFE of 10^{-4}, with a stop at median displacement for 220% DBE shaking.

Table 14. Annual frequency of unacceptable performance ($\times 10^{-6}$) of individual isolator units tested at median displacement for 220% DBE shaking, with a stop at median displacement for 220% DBE shaking.

	Site							
Confidence	North Anna	Summer	Vogtle	Oak Ridge	Hanford	Idaho	Los Alamos	Diablo Canyon
90%	2.4	1.5	1.3	2.0	0.9	0.7	2.1	0.6
95%	1.2	0.7	0.6	1.0	0.4	0.4	1.1	0.3
99%	0.2	0.1	0.1	0.2	0.1	0.1	0.2	0.1

The derivation of the *DF* in ASCE 43 focuses on the effects of horizontal earthquake shaking. The vertical elements in the gravity and lateral load resisting systems in an NPP such as AP1000 (Schulz, 2006) are walls and not columns, for which failure due to excessive vertical loading is extremely unlikely because design axial stresses are very low. A much greater seismic margin is expected in the vertical direction than the horizontal direction. Since the vertical seismic demands in an isolated NPP should be no greater than those in a conventionally founded (fixed-base) NPP, there is no need to increase the vertical UHRS by a *DF* to compute the GMRS. Seismically isolated nuclear structures with columns providing much of the vertical load resistance (regardless of cause) should be evaluated for shaking in excess of design basis to ensure their annual frequency of unacceptable performance is less than the target performance goal.

9. Summary and conclusions

Seismic hazard definitions and performance goals for conventionally founded and seismically isolated NPPs are reviewed. Seismic risk associated with the isolated superstructure, isolation system and umbilical lines in seismically isolated NPPs are estimated using the seismic hazard data reported on the USGS website and assuming that the performance goals outlined in 1) the forthcoming NUREG/CR, and 2) ASCE Standard 4 are satisfied. The risk associated with the horizontal shaking of the isolated superstructure with a certified design in accordance with the provisions for the conventionally founded NPPs is considered small. It is further assumed that the risk associated with vertical shaking is identical for the conventionally founded and seismically isolated NPPs. The performance requirements for the isolation system and umbilical lines are similar. The risk for the isolation system is computed in terms of annual frequency of unacceptable performance. Fragility curves are developed assuming (very conservatively) that the performance of an individual isolator unit represents the performance of the isolation system. Three risk mitigation strategies are considered, namely, 1) testing the isolators with greater confidence, 2) testing the isolators at a greater displacement, and 3) providing a stop.

The mean annual frequency of unacceptable performance of individual bearings designed and tested per the forthcoming NUREG/CR is calculated at eight nuclear facility sites in the United States. Companion calculations are performed for SDC 5 nuclear structures per ASCE Standard 43-05. Median fragility curves are conservatively (overestimating risk) derived by setting the 90^{th} percentile displacement for BDB GMRS shaking (or 150% DBE shaking per ASCE 43) equal to the median displacement for 110% BDB GMRS shaking (or 165% DBE shaking in ASCE 43).

The mean annual frequency of unacceptable performance of individual isolators (and umbilical lines) tested in accordance with the forthcoming seismic isolation NUREG/CR (i.e., 90% confidence at 90^{th} percentile displacement for BDB GMRS shaking) ranges between 4.7×10^{-6} and 7.3×10^{-6} (values substantially greater than the target goal of 1×10^{-6}) for the eight sites, if a stop is not provided. The risk is reduced in a meaningful manner if testing is performed to either the same displacement but higher confidence or the same confidence and greater displacement, but remains greater than 1×10^{-6}. The introduction of a stop at the 90^{th} percentile displacement for BDB GMRS shaking achieves the goal of driving the risk below 1×10^{-6}. If the confidence level is increased from 90% to 99%, the risk drops well below 1×10^{-7}.

A stop is generally needed to reduce the annual frequency of unacceptable performance of a DOE-regulated SDC 5 isolated safety-related nuclear structure below the target goal of 1×10^{-5}.

The GMRS in USNRC-regulated facilities and the design response spectrum in DOE facilities are calculated for design of NPPs (and other SDC 5 structures) by multiplying the ordinates of a uniform hazard response spectrum at the specified hazard exceedance frequency by a DF that is greater than or equal to 1.0. The factor can be set equal to 1.0 for design of a seismically isolated NPP if the earthquake risk is dominated by horizontal ground shaking and a stop is provided.

Epilogue

The ASCE Committee on the Dynamic Analysis of Nuclear Structures is currently revising ASCE 43. One provision that has already been balloted and passed (as of June 2016) is an update to the calculation of the DRS. In ASCE 43, and as summarized in Section 3.1, the DRS is established by multiplying the ordinates of the UHRS at the specified hazard exceedance probability by DF. In the next edition of ASCE 43, the DRS will be established by reducing the target performance goal by a scale factor. The scale factor and DF are closely related. The ordinates of the DRS will not be altered by this change in calculation. The ordinates of the DRS for seismically isolated NPPs will remain those of the UHRS calculated for a hazard exceedance probability of 1×10^{-4}.

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References

American Concrete Institute (ACI) (2013a). Code requirements for nuclear safety-related concrete structures and commentary. ACI Standard 349-13, Farmington Hills, MI.

American Concrete Institute (ACI) (2013b). Code for concrete containments. ACI Standard 359-13, Farmington Hills, MI.

American Institute of Steel Construction (AISC) (2012). Specification for safety-related steel structures for nuclear facilities. ANSI/AISC N690-12, Chicago, IL.

American Nuclear Society (ANS) (2010). Categorization of nuclear facility structures, systems, and components for seismic design. ANSI/ANS-2.26-2004, La Grange Park, IL.

American Society of Civil Engineers (ASCE) (2005). Seismic design criteria for structures, systems and components in nuclear facilities. ASCE/SEI Standard 43-05, Reston, Virginia.

American Society of Civil Engineers (ASCE) (2016). Seismic analysis of safety-related nuclear structures and commentary. ASCE/SEI Standard 4-16, Reston, Virginia.

United States Department of Energy (DOE) (1994). Natural phenomena hazards design and evaluation criteria for Department of Energy facilities. DOE-STD-1020-94, Washington, D.C.

Huang, Y.-N., Whittaker, A. S., and Luco, N. (2010). Seismic performance assessment of base-isolated safety-related nuclear structures. Earthquake Engineering & Structural Dynamics, 39(13), 1421-1442.

Kammerer, A., Whittaker, A., and Constantinou, M. (forthcoming). Technical considerations for seismic isolation of nuclear facilities. Report NUREG/CR-****, United States Nuclear Regulatory Commission, Washington, D.C.

Kumar, M., Whittaker, A. S., and Constantinou, M. C. (2015). Seismic isolation of nuclear power plants using sliding bearings. Report MCEER-15-0006, University at Buffalo, The State University of New York, Buffalo, NY.

Schulz, T. L. (2006). Westinghouse AP1000 advanced passive plant. Nuclear Engineering and Design, 236(14–16), 1547-1557.
United States Atomic Energy Commission (USAEC) (1973). Design response spectra for seismic design of nuclear power plants. Regulatory Guide 1.60, Washington, D.C.
United States Nuclear Regulatory Commission (USNRC) (2007a). A performance-based approach to define the site-specific earthquake ground motion. Regulatory Guide 1.208, Washington, D.C.
United States Nuclear Regulatory Commission (USNRC) (2007b). Standard review plan for the review of safety analysis reports for nuclear power plants. NUREG-0800, Washington, D.C.
United States Nuclear Regulatory Commission (USNRC) (2014). Design response spectra for seismic design of nuclear power plants. Regulatory Guide 1.60, Washington, D.C.