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ASCE 4 PROVISIONS FOR SEISMIC ISOLATION OF SAFETY-RELATED NUCLEAR STRUCTURES

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ABSTRACT

Seismic isolation is a viable method of protecting nuclear safety-related structures from the damaging effects of earthquake shaking. The soon-to-be completed 2013 edition of ASCE Standard 4 will include detailed provisions and commentary (Section 7.7) to enable the horizontal seismic isolation of nuclear facilities such as nuclear power reactors and waste storage facilities. Although the provisions and commentary focus on building-type structures, they can be applied, in principle, to other structures, systems, and components, including small modular reactors and safety-related systems such as diesel generators. The performance expectations associated with the provisions, and their integration with ASCE 43-05, are presented together with the design basis for the isolated superstructure and safety-related secondary systems, the isolators, the foundation and the umbilical lines that cross the isolation interface.

INTRODUCTION

Figure 1 identifies components of a seismically isolated nuclear structure. The isolators (also termed isolator units and bearings) are assumed installed in a near horizontal plane beneath a basemat that supports the nuclear construction, which is defined as the superstructure. The isolators are installed atop pedestals and a foundation, which is defined as the substructure. The moat is a space in which the isolated superstructure can move without restriction in the event of earthquake shaking.

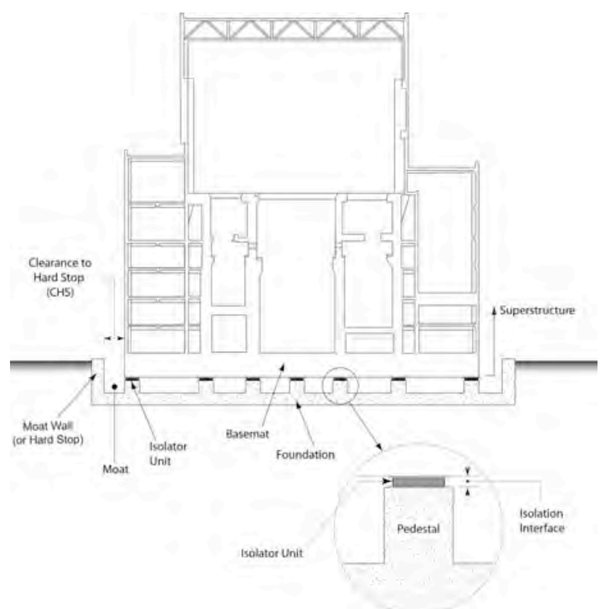

Figure 1. A seismically isolated nuclear structure (USNRC 2013)

The USNRC is sponsoring the development of a NUREG on seismic isolation of nuclear power plants (USNRC 2013). The guidance provided in the NUREG, which should be released around the time of the SMiRT conference, is similar in many regards to Section 7.7, although a different definition is used for Beyond Design Basis Earthquake shaking.

The mandatory language and commentary to Section 7.7 are based in part on provisions and commentary developed for the seismic isolation of buildings (ASCE 2010, FEMA 2010) and bridges (AASHTO 2010), and the reader is referred to these standards and guidelines for additional information.

The paper describes the analysis and design procedures that can be used to implement a seismic isolation system in a safety-related nuclear structure. Emphasis is placed in the paper on how the risk-based performance objectives of ASCE 43 are achieved; the analysis of the isolation system, addressing soil-structure interaction; displacements and forces used for design of the facility; and the required prototype and production testing of seismic isolators. The types of isolators considered sufficiently mature for nuclear applications in the United States and requirements for qualification of a new type of isolator or isolation system are identified.

RISK-INFORMED DESIGN

The performance expectations of Section 1.3 of ASCE 43 (ASCE 2005) form the basis of the provisions of Section 7.7 of ASCE 4, namely, 1) 1% probability of unacceptable performance for 100% DBE shaking, and 2) 10% probability of unacceptable performance for 150% DBE shaking. Beyond Design Basis Earthquake (BDBE) shaking is defined as 150% DBE shaking. Consistent with other sections of ASCE 4, seismic demands on the isolated superstructure are calculated at the 80th percentile level for DBE shaking.

A significant difference between Section 7.7 of ASCE 4 and companion provisions for buildings (ASCE 2010) and bridges (AASHTO 2010) is the introduction of a physical stop. The stop, which can be a *moat* wall, is used to prevent excessive displacement of the isolation system and removes the isolation system from accident sequences involving earthquake shaking. The unrestricted travel (displacement) of the isolation system is defined as the clearance to the stop, *CS*.

Table 1 summarizes the performance expectations for seismically isolated nuclear structures. Analysis is performed for DBE and BDBE shaking. Seismic demands are calculated at the 80th percentile level for DBE shaking and the 90th percentile level for BDBE shaking. Results of DBE analysis are used for a) calculating design loads on the superstructure, b) generating in-structure response spectra for design of structures, components and systems (SSC), and c) establishing displacements for production testing of isolators. Results of BDBE (150% DBE) analysis are used to a) select the required clearance to the physical stop, and b) establish displacements and forces for prototype testing of isolators.

Four performance statements for achieving the two performance objectives of ASCE 43 were assumed in the writing of Section 7.7, namely, 1) individual isolators shall suffer no damage in DBE shaking, 2) the probability of the isolated nuclear structure impacting surrounding structure or the moat wall for 100% (150%) DBE shaking shall be 1% (10%) or less, 3) individual isolators shall sustain gravity and earthquake-induced axial loads at 90th percentile lateral displacements consistent with 150% DBE shaking, and 4) the probability of unacceptable performance in the isolated superstructure for 100% (150%) DBE shaking shall be 1% (10%) or less. Performance statement 1 is realized by production testing of each isolator supplied to a project for the 80th percentile DBE displacement and co-existing gravity and earthquake-induced axial forces. Analysis can be used in support of performance statement 2 provided that the isolators are modeled correctly and the ground motion representations are reasonable. (Huang et

		Isolation system			Superstructure	Other SSCs		
Hazard	**Use**	**Isolation system displacement**	**Performance**	**Acceptance criteria**	**Performance**	**Performance**	**Umbilical lines**	**Hard Stop or Moat**
DBE Response spectrum per Chapter 2	Production testing of isolators. Design loads for isolated superstructure. In-structure response spectra (ISRS).	Mean and 80th percentile isolation system displacements.	No damage to the isolation system for DBE shaking.	Production testing of each isolator for the 80th percentile isolation system displacement and corresponding axial force. Isolators damaged by testing cannot be used for construction.	Conform to consensus materials standards for 80th percentile demands. Greater than 99% probability that component capacities will not be exceeded. Greater than 99% probability that the superstructure will not contact the moat.[1]	Conform to ASME standards for 80th percentile demands; adjust ISRS per Section 6.2.3. Greater than 99% probability that component capacities will not be exceeded.	-	-
BDBE 150% of DBE	Prototype testing of isolators. Selecting moat width (or Clearance to Stop).	90th percentile isolation system displacement.[2]	Greater than 90% probability of the isolation system surviving BDBE shaking without loss of gravity-load capacity.	Prototype testing of a sufficient[3] number of isolators for the CS displacement and the corresponding axial force. Isolator damage is acceptable but load-carrying capacity is maintained.	Greater than 90% probability that the superstructure will not contact the moat. Achieved by setting the moat width equal to or greater than the 90th percentile displacement. Greater than 90% probability that component capacities will not be exceeded.	Greater than 90% probability that component capacities will not be exceeded.	Greater than 90% confidence that all safety-related umbilical lines and their connections, shall remain functional for the CS displacement by testing, analysis or a combination of both.	Clearance to Stop (CS) or moat width equal to or greater than the 90th percentile displacement. Damage to the moat is acceptable in the event of contact.

1. Can be achieved by satisfying the requirement for BDBE shaking.

2. 90th percentile BDBE displacements may be calculated by multiplying the mean DBE displacement by a factor of 3.

3. The number of prototype isolators to be tested shall be sufficient to provide the required 90+% confidence.

Table 1. Minimum performance expectations for seismically isolated nuclear structures

al. (2009, 2012) showed that the 90th percentile displacement for 150% DBE shaking is greater than 99th percentile displacement for DBE shaking and so the former is used to establish the clearance to the stop, *CS*.) Performance statement 3 is achieved by prototype testing of a limited number of isolators at a displacement equal to *CS* and co-existing axial forces, noting that an isolation system is composed of tens to hundreds of isolators and that failure of the isolation sytem would have to involve the simultaneous failure of a significant percentage of the isolators in the system. Performance statement 4 is checked by analysis of the capacity of the isolated superstructure at 100% DBE and BDBE shaking using procedures presented in Section 1 of ASCE 4 and in the commentary to ASCE 43. If the probabilities of failure at DBE and BDBE shaking exceed the limits of Section 1.3 of ASCE 43, the capacity (strength) of the isolated superstructure is increased until the performance statement is achieved. Adequate performance of the foundation is achieved by designing for forces delivered by the isolation system at displacement *CS*, as described later.

ANALYSIS OF SEISMICALLY ISOLATED NUCLEAR STRUCTURES

Three methods can be used for analysis of seismically isolated nuclear structures: 1) time domain, 2) frequency domain, and 3) multi-step. Each method involves soil-structure-interaction analysis for which guidance is provided in Section 5 and Appendix B of ASCE 4.

Three-dimensional models must be prepared and subjected simultaneously to three translational components of ground motion. The goals of dynamic analysis are to generate displacements and forces at the 80th percentile level for DBE shaking and at the 90th percentile level for BDBE shaking.

Time-domain analysis

Nonlinear time-domain analysis of a soil-foundation-isolator-superstructure system may be performed for any type of isolation system. Nonlinear finite elements must be used for all components in the mathematical model that are expected to respond inelastically for the chosen intensity of shaking.

The finite element meshes for the foundation and superstructure should be similar to those used for non-isolated construction and be capable of transmitting frequencies across the range of interest for the SSCs. Finite element meshes shall be developed for best estimate (BE), upper bound (UB) and lower bound (LB) soil properties per Chapter 2 of ASCE 4. Isolators will generally be modeled as beam elements connecting the foundation (or pedestal) to the basemat. Each isolator in the isolation system must be modeled explicitly.

Five or more independent sets of three-component acceleration time series are generated for time-domain analysis per Chapter 2 and Section 4.7 of ASCE 4. Analysis is performed using each time series and each soil mesh (BE, UB, LB). The mean maximum response for the intensity of shaking is taken as the average of the maximum responses. The 80th percentile maximum DBE demand is taken as the maximum of the mean DBE demands calculated for the three soil meshes. Distributions of demands can be calculated directly using ten or more independent sets of time series and the three soil meshes. The 90th percentile BDBE demands can also be calculated directly from a distribution or by factoring mean DBE demands per Huang et al. (2009).

Floor spectra for analysis and design of equipment supported above the isolation interface are generated from the results of the nonlinear response-history analysis. Such spectra must then be modified per other sections of ASCE 4 for the purpose of equipment qualification.

Frequency domain analysis

Frequency-domain analysis involves the calculation of equivalent linear properties for all components in the mathematical model. This analysis procedure can be used for proportioning a safety-related nuclear facility equipped with isolators that can be modeled accurately as linear viscoelastic elements for the chosen intensity of shaking. This analysis procedure can be used in the first step of the multi-step method if nonlinear isolators are being used.

Five or more independent sets of three component acceleration time series are generated per Chapter 2 of ASCE 4 for analysis of each soil profile (BE, UB, LB). Mean and 80th percentile DBE demands and 90th percentile BDBE demands are calculated as described above.

The equivalent linear properties chosen for analysis of a nuclear facility a) shall be shown to be appropriate following the analysis, and b) form a basis of the prototype- and production-testing programs for the isolators. Floor spectra for analysis and design of equipment supported above the isolation interface are generated from the results of the analysis and then modified as noted above.

Multi-step method

The multi-step method involves two analyses: 1) propagation of rock outcrop ground motion into a model of a soil-foundation-isolator-superstructure system for the purpose of generating Seismic Isolation Design Response Spectra (SIDRS) at the level of the foundation (see Figure 1), and 2) nonlinear response-history analysis of a model of the isolated superstructure using three-component acceleration time series consistent with the SIDRS. This analysis procedure can be used for all types of isolation systems.

The generation of SIDRS using frequency-domain procedures requires the development of equivalent linear properties for the isolators. Section 7.7.4.2 of ASCE 4 provides guidance on these calculations. Aside from the isolators, the mathematical models (e.g., soils, structure) and analysis procedures used to generate the SIDRS should be identical to those models and procedures used for conventional (non-isolated) nuclear structures. The equivalent linear properties chosen for the isolators should be shown to be appropriate following the second step of the multi-step analysis.

To generate SIDRS, frequency domain analysis is performed per Chapter 5 of ASCE 4, as summarized above. SIDRS are generated at the mean and 80th percentile levels for DBE shaking. A mean SIDRS is calculated by averaging the spectral demand computed for each acceleration time series and each soil column, frequency by frequency. An 80th percentile SIDRS is calculated by enveloping the three mean spectra: one spectrum for each soil column.

Nonlinear time-domain analysis of the isolated structure is the second step in the multi-step procedure. Acceleration time series are generated to be consistent with the SIDRS. Three-component translational time series must be derived and rotational (rocking) time series should be included if such motions are shown to be of significance by the soil-structure interaction analysis in step one. The procedures for nonlinear analysis follow those described above for time-domain analysis. To compute mean DBE demands, five or greater sets of motions are generated, consistent with the mean DBE SIDRS. To compute 80th percentile DBE demands, five or greater of motions are generated, consistent with the 80th percentile DBE SIDRS. Averaged demands from these analyses are used for design. Two methods may be used to compute demand at the 90th percentile level for BDBE shaking: 1) generate a minimum of 10 sets of motions consistent with the mean BDBE SIDRS, analyze the isolated structures using the three soil meshes, establish a distribution of demand, and compute the 90th percentile, or 2) factor the mean DBE demand per Huang et al. (2009). Floor spectra for analysis and design of equipment supported above the isolation interface are generated for mean or 80th percentile DBE shaking from the results of the nonlinear response-history analysis, and then modified as needed for equipment qualification.

DISPLACEMENTS AND FORCES FOR DESIGN

Seismic isolators

The mechanical properties of the isolators are established by prototype and production testing, as described below. The connections of the isolators to the substructure and superstructure are designed to resist the forces delivered by the isolation system at a displacement equal to the clearance to the stop (*CS*) to confine nonlinear response to the isolators and to ensure the isolation system does not form part of any accident sequence. The load factors and strength reduction factors presented in materials standards shall be used for design of these steel and reinforced concrete components.

Stop

The Clearance to Stop (*CS*) is the 90th percentile BDBE displacement, which will exceed the clearances to the stop along the horizontal axes used to define the seismic input, but will not be greater than the vector sum of the two clearances.

The stop is designed for impact by the isolated superstructure. Standard ACI 349 should be used for this purpose. The velocity at impact may be calculated by either analysis for BDBE ground motions or by assuming cyclic response of the isolated superstructure to the 95th percentile BDBE displacement at a frequency equal to the that calculated for the isolation system assuming the best-estimate second-slope stiffness (K_d in Figure 2 for LR and FP isolation systems) and the reactive weight of the superstructure.

SSCs above the isolation interface

The design of the SSCs above the isolation interface should be based on the results of response-history analysis for DBE shaking at the 80th percentile level. Calculations should be performed to demonstrate that the performance expectations of Section 1.3 of ASCE 43 are achieved. If the failure probabilities exceed either 1% for DBE shaking or 10% for BDBE shaking, the design forces are increased to reduce the failure probabilities to the limiting values.

The basemat and the foundation must be sufficiently stiff to engage all of the isolators in the gravity load resisting system and seismic force-resisting system. The basemat shall be designed to resist gravity loads assuming the loss of one isolator due to the local vertical settlement of the foundation below the isolation system. Multiple calculations, assuming the loss of a different isolator in the system, will be required.

Structure below the isolation interface

To ensure nonlinear response is confined to the isolators, the design of the foundation should be based on the forces delivered by the isolators at an isolation-system displacement equal to *CS*. The load factors and strength reduction factors presented in materials standards such as ACI 349 (ACI 2006) shall be used for design.

Systems and components crossing the isolation interface

Umbilical lines are systems and components that cross the isolation interface and may serve a safety-related function. The probability of failure of these umbilical lines should be less than 10% in BDBE shaking (and also 1% in DBE shaking, which will not control as noted previously). The umbilical lines should be capable of sustaining a displacement equal to *CS* and remain functional, with 90% confidence. Numerical simulations, full-scale dynamic testing, or a combination thereof, can be used to demonstrate adequacy.

PROTOTYPE AND PRODUCTION TESTING OF ISOLATORS

Two types of tests are performed on seismic isolators: 1) prototype, and 2) production. The prototype and production tests focus on horizontal seismic response of isolators. Tests may be required to confirm the mechanical properties of an isolator in the vertical (axial) direction.

Prototype tests are performed on a small number of isolators of each type planned for use in the isolation system. These tests are conducted prior to isolator production for the project. The purpose of the tests is to ensure that the isolators perform as anticipated for DBE and BDBE shaking. Dynamic testing at a frequency equal to that of the isolated superstructure is required for some prototype tests, because the static and dynamic properties of an isolator will generally be different. Testing at a displacement equal to the clearance to the stop is required to demonstrate isolator capacity under extreme loadings. The acceptance criteria used for prototype bearing tests should be consistent with the assumptions made for the design of the seismic isolators and seismic isolation system, and shall therefore be developed on a project-by-project basis. Basic acceptance criteria for the three prototype tests are provided. Sample criteria can also be found in ASCE 7 (ASCE 2010) and the AASHTO Guide Specification for Seismic Isolation Design (AASHTO 2010). If a prototype isolator fails to meet the acceptance criteria, all prototype isolators of that type and size are rejected and another three specimens must be fabricated for prototype testing.

Production (or quality control) tests are performed on each isolator fabricated for a project. The production-testing program is less onerous than the prototype-testing program: dynamic tests are not required and the test displacement is that computed for the 80th percentile DBE displacement. Project-specific acceptance criteria will generally be developed for the production testing of isolators. For each type and size of bearing, shearing force-lateral displacement relationships should range between the limits specified by the designer. A minimum vertical stiffness for each type and size of isolator should be specified. The acceptance criteria used for production bearing tests should be consistent with the assumptions made for the design of the seismic isolators and seismic isolation system, and are developed on a project-specific basis.

A quality assurance program shall be prepared for the seismic isolators. The program shall follow ASME-NQA-1 (ASME 2008, 2011) or an approved equivalent.

ISOLATORS AND ISOLATION SYSTEMS

Three types of isolators have been qualified for use in safety-related nuclear structures: low damping (natural) rubber (LDR) isolators, lead (natural) rubber (LR) isolators, and the Friction Pendulum (FP) sliding isolators. Each has been tested extensively, can be modeled for nonlinear response-history analysis, and has been deployed in mission-critical structures in the United States. The mechanical characteristics of these isolators (linear and bilinear) underpin the rules set forth in Section 7.7. The assumed hysteretic response of LR and FP bearings in the horizontal direction is presented in Figure 2.

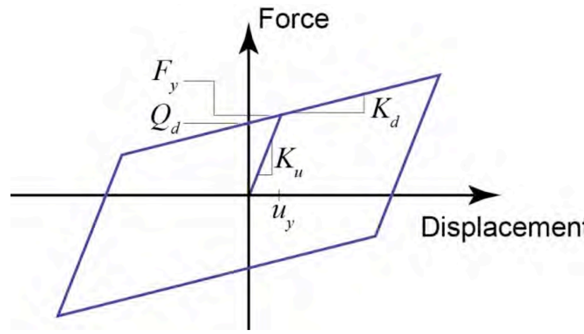

Figure 2. Assumed hysteretic response of LR and FP bearings in a horizontal direction

Low-damping (LD) elastomeric bearings are composed of alternating layers of natural rubber and steel, and can be modeled as viscoelastic components. The shear modulus of the rubber ranges between 60 psi and 120 psi. The equivalent viscous damping is between 2 and 4% of critical. Lead-rubber (LR) elastomeric bearings are constructed similarly to low-damping rubber bearings but include a central lead core to dissipate earthquake-induced energy. The hysteresis loop for the LR bearing is bilinear per Figure 2 and defined by a zero-displacement force intercept, Q_d, an elastic stiffness, K_u and a second-slope stiffness, K_d, where W is the supported weight. Sliding bearings with restoring force provided by gravity also have the hysteresis loop of Figure 2. In the Friction Pendulum™ (FP) family of bearings, the second-slope stiffness is related to the supported weight and the radius of curvature of the sliding surfaces. Constantinou et al. (2007) and Naeim and Kelly (1999) provide information on LD, LR and FP seismic isolators. Huang et al. (2008, 2009, 2010, 2012) provide data and information in support of the isolation of nuclear structures and the provisions of this section. Constantinou et al. (1999, 2007), Thompson et al. (2000) and Morgan and Whittaker (2001) provide the data used by Huang et al. (2009, 2012) to characterize the impact of variations in isolator material properties on the displacement response of seismic isolation systems.

Other types of isolators from the three mentioned above are not precluded from use in safety-related nuclear structures. However, the following tasks must be undertaken to qualify another type of isolator (or isolation system) for use in a safety-related nuclear structure:

1. Dynamic testing of full-scale (prototype) isolators for compressive and tensile axial loads and bidirectional horizontal motion at amplitudes of displacement expected for beyond design basis ground motions in regions of moderate and high seismic hazard;
2. Development of verified and validated numerical models capable of predicting the results of dynamic testing of prototype isolators, including deterioration of hysteresis due to energy dissipation during earthquakes;
3. Demonstration through basic chemistry, laboratory tests and field applications that the mechanical properties of the isolators do not change by more than 20% over a 50- to 100-year period in the temperature range of 40°F to 80°F;
4. System-level testing of the isolation system using three translational components of earthquake ground motion;

5. Verification and validation of numerical tools and codes to predict the seismic response of the isolation system; and
6. Deployment of an isolation system composed of the isolators in mission-critical structures.

Section 7.7 requires tasks 1 through 5 to be performed by experienced persons, independent of the isolator manufacturer. Hybrid isolation systems involving different types of bearing (e.g., sliding and elastomeric) are not permitted.

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REFERENCES

American Association of State Highway and Transportation Officials (AASHTO). (2010). "Guide specification for seismic isolation design." Washington, D.C.

American Concrete Institute (ACI). (2006). "Code requirements for nuclear safety-related structures." *ACI 349-06*, Farmington Hill, MI.

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

American Society of Civil Engineers (ASCE). (2010). "Minimum design loads for buildings and other structures." *ASCE/SEI 7-10*, Reston, VA.

American Society of Mechanical Engineers (ASME). (2008). "Quality assurance requirements for nuclear facility applications." *ASME NQA-1*, New York, NY.

American Society of Mechanical Engineers (ASME). (2011). "Quality assurance requirements for nuclear facility applications; addenda to ASME NQA-1-2008." *ASME NQA-1b*, New York, NY.

Constantinou, M. C., Tsopelas, P., Kasalanati, A., and Wolff, E. D. (1999). "Property modification factors for seismic isolation bearings." *MCEER-99-0012*, State University of New York, Buffalo, NY.

Constantinou, M. C., Whittaker, A. S., Kalpakidis, Y., Fenz, D. M., and Warn, G. P. (2007) "Performance of seismic isolation hardware under service and seismic loading." *MCEER-07-0012*, State University of New York, Buffalo, NY.

Federal Emergency Management Agency (FEMA). (2010). "NEHRP recommended provisions for seismic regulations for new buildings and other structures." *FEMA 750-1/2009 Edition (Provisions) and 750-2/2010 Edition (Commentary)*, Washington, D.C.

Huang, Y.-N., Whittaker, A. S., and Luco, N. (2008). "Performance assessment of conventional and base-isolated nuclear power plants for earthquake and blast loadings." *MCEER-08-0019*, State University of New York, Buffalo, NY.

Huang, Y.-N, Whittaker, A. S., Kennedy, R. P. and Mayes, R. L. (2009). "Assessment of base-isolated nuclear structures for design and beyond-design basis earthquake shaking." *MCEER-09-0008*, State University of New York, Buffalo, NY.

Huang, Y.-N., Whittaker, A. S. and Luco, N. (2010). "Seismic performance assessment of base-isolated safety-related nuclear structures." *Earthquake Engineering and Structural Dynamics*, Vol. 39, No. 13, pp. 1421-1442.

Huang, Y.-N., Whittaker, A. S., Kennedy, R. P. and Mayes, R. L. (2012). "Response of base-isolated nuclear structures for design basis and beyond design basis earthquake shaking." *Earthquake Engineering and Structural Dynamics*, DOI:10.1002/eqe. 2209.

Morgan, T., Whittaker, A. S. and Thompson, A.C. (2001). "Cyclic behavior of high-damping rubber bearings." *Proceedings*, Fifth World Congress on Joints, Bearings and Seismic Systems for Concrete Structures, American Concrete Institute, Rome, Italy.

Naeim, F., and Kelly, J. M. (1999). *Design of seismic isolated structures: from theory to practice*, John Wiley, NY.

Thompson, A., Whittaker, A. S., Fenves, G. L. and Mahin, S. A. (2000). "Property modification factors for elastomeric bearings. " *Proceedings*, Twelfth World Conference on Earthquake Engineering, Auckland, New Zealand.

United States Nuclear Regulatory Commission (USNRC). (2013). "Technical considerations for the seismic isolation of nuclear facilities." forthcoming NUREG, Washington DC.