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SEISMIC ISOLATION OF NUCLEAR POWER PLANTS: PAST, PRESENT AND FUTURE

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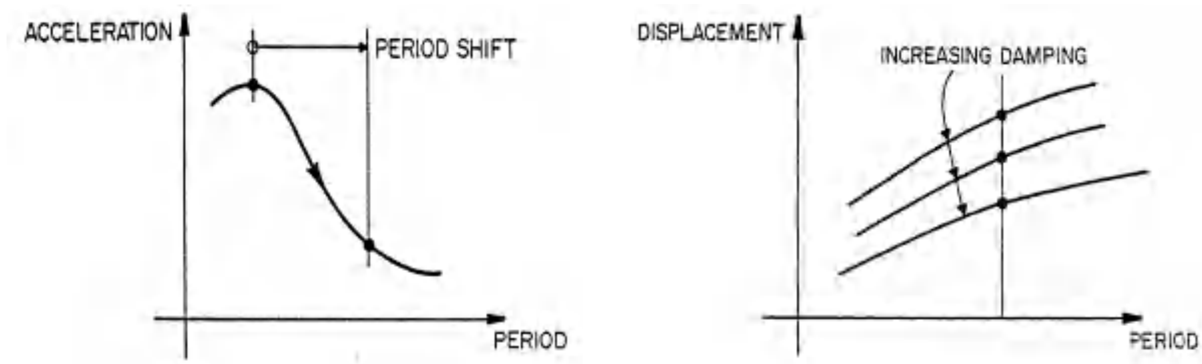
ABSTRACT

Seismic isolation of nuclear power plants is in its infancy, with only a small number of applications worldwide. This outcome is due in part to the construction of only a small number of new build nuclear power plants since the technology became mainstream in the 1990s, perceived concerns regarding the long-term mechanical properties of isolation bearings, and a lack of guidance, codes and standards related to isolation of safety-related nuclear facilities. This paper charts the history of seismic isolation, identifies the research that led to the first implementation of isolation for buildings and bridges in the modern era, summarizes the first applications of the technology to nuclear facilities, and describes important research and developments, and the writing of regulatory standards, in the past 20 years. Future research and development needs are identified.

INTRODUCTION

This paper has broad goals, many in support of the state-of-the-art session on seismic isolation at the 24th International Conference on Structural Mechanics in Reactor Technology, held in Busan, South Korea, in August 2017. One purpose of this paper is to compile and distil information on seismic isolation developed by researchers and practitioners in the modern era, with a focus on applications to nuclear structures (including nuclear power plants) and nuclear safety. A second goal is to identify recent developments in the field in the United States, Europe, Korea, and Japan with which some practitioners might not be familiar. A third goal is to be forward looking, which involves identification of future opportunities and technical needs.

Seismic isolation of buildings, nuclear facilities, infrastructure and bridges typically involves the installation of vertically stiff and horizontally flexible devices (hereafter described as isolators or bearings) beneath the points of gravity-load support. Isolation is generally provided in the horizontal direction only. Figure 1 illustrates the effect of installing a horizontal isolation system beneath a building, namely, a period shift (increase) that reduces horizontal spectral acceleration (Figure 1a), and an increase in horizontal spectral displacement that is typically mitigated by the addition of energy dissipation or damping (Figure 1b). Nearly all of the spectral displacement is accommodated over the height of the seismic isolators and the drift demand on the superstructure is substantially smaller in the isolated building than in its conventional (non-isolated) counterpart.



a. reduction in spectral acceleration b. increase in spectral displacement

Figure 1. Principles of horizontal seismic isolation (courtesy of Dynamic Isolation Systems)

Figure 2 presents images of two types of seismic isolator used in the United States: the lead-rubber (elastomeric) bearing in Figure 2a, and the single-concave Friction Pendulum™ bearing in Figure 2b. The cutaway view of the lead rubber (LR) bearing shows its internal construction, namely, alternating layers of *natural* rubber and steel shims. A lead core (or plug) in the center of the bearing is installed to provide robust energy dissipation, which aids in reducing the horizontal displacement of the seismic isolation system. The diameter of the lead core ranges between one-sixth and one-third of the bonded diameter of the elastomeric bearing. The natural rubber in this bearing, which provides the horizontal flexibility, has a shear modulus of between 60 psi (0.41 MPa) and 100 psi (0.69 MPa); the damping in the *natural rubber* of the bearing is between 2% and 4% of critical. The damping in the bearing is more a function of the diameter of the lead core, the dynamic yield strength of the lead, and the horizontal displacement of the bearing, with respect to its at-rest position. A lead core is not necessarily needed in a bearing if the horizontal displacement demands are small. Such a bearing is described here as a low-damping rubber (LDR) bearing. The LR, LDR and FP bearings are deemed appropriate for use in nuclear facilities in the United States (ASCE 2017, Kammerer et al. 2017) because their mechanical properties are stable and well characterized.

The two images in Figure 2b show the parts of the single-concave Friction Pendulum (FP) bearing. This bearing, with a rated axial load capacity greater than 15,000 tonnes, was used as part of a four-bearing seismic isolation system for an offshore platform. The upper part, known as the housing plate, is inverted upon installation and placed atop the hemispherical (articulated) slider seen in the lower part. Horizontal isolation is achieved as the articulated slider moves across the concave sliding surface, seen below the slider in the lower part of the figure. The assembly (housing plate, slider, concave sliding surface) can be installed with the housing plate at the bottom or the top, and this will dictate how second-order moments are shared between the substructure and the isolated superstructure (e.g., Mosqueda et al. 2004a, 2004b).

a. lead-rubber bearing b. single concave Friction Pendulum™ bearing

Figure 2. Types of seismic isolation bearings

There are a number of variations on the isolators of Figure 2 that are used outside of the United States. The low-damping rubber in the bearing of Figure 2a can be replaced with high-damping rubber (HDR) or a synthetic rubber. High-damping rubbers, with damping of the order of 10% to 12% of critical, have been used for some applications in Japan. Polychloroprene rubber has been used in bearings fabricated in France for application to nuclear facilities since the early 1980s (AFCEN 2015, Labbe 2010); the damping in this synthetic elastomer is of the same order as that in a natural rubber.

Variations on the single concave bearing of Figure 2b include the double concave FP bearing (two concave sliding surfaces; see Fenz and Constantinou 2006) and the triple FP bearing (see Fenz and Constantinou 2008a, 2008b; Sarlis and Constantinou 2016). The chief attribute of the double concave bearing is compactness: because sliding is achieved on two surfaces simultaneously, its overall diameter is much smaller than that of the single concave bearing for a given displacement capacity. The triple FP bearing enables trilinear hysteresis, which is potentially useful for seismic isolation systems not equipped with a stop.

Three-dimensional isolation systems have been applied in a limited number of cases to diesel generators and spent fuel pools in nuclear power plants in Switzerland (Nawrotzki et al. 2009). The components of these systems are vertically installed steel springs and viscous dashpots. Applications have been limited to sites of low seismic hazard.

HISTORICAL DEVELOPMENTS

Constantinou (2017) chronicled historical developments of seismic isolation, although those applications did not utilize the seismic isolation devices described above. A rudimentary sliding system was employed in Persia around 530 BC for the Tomb of King Cyrus the Great (stone blocks above the foundation installed without mortar to allow sliding). Monolithic columns permitted to rock were used to construct the Temple of Apollo in Corinth, Greece around 540 BC and the Library of Celsus in Ephesos, Turkey around 120 AD. The Obelisk of Theodosius, originally erected in Egypt around 1450 BC, was transported to Constantinople and re-erected in the hippodrome, on a marble base equipped with rocking supports and a sliding foundation. More recent developments include a US patent to Joules Touaillon in 1870 for an isolation system composed of a substructure and a superstructure, each with multiple, vertically aligned, hemispherical sliding surfaces, separated by one sphere per pair of surfaces: similar in some regards to the double concave FP bearing. Patents were also issued in 1907 to J. Bechtold and Dr.

Calantarients for (impractical) isolation systems involving a foundation supported by a bed of spheres and a foundation sliding on talc, respectively. A three-story apartment building, with columns supported by cables, was constructed in 1955 in Ashkhabad, Turkmenistan (then the Soviet Union), and was the first isolation system involving devices: similar in operation to an undamped FP isolation system. Soviet engineers continued the development of isolators in the 1960s, with roller bearings of different shapes, and with rocking columns.

EARLY DEVELOPMENTS IN THE MODERN ERA

Seismic isolation research, non-nuclear

Interest and key developments in the modern era related to seismic isolation in the United States is traced to a) studies in New Zealand in the early 1970s, and b) subsequent studies by Kelly and his co-workers on elastomeric bearings at the University of California, Berkeley, by Mahin on sliding bearings also at the University of California, Berkeley, beginning in the mid 1980s, and by Constantinou and Reinhorn at the University at Buffalo, on sliding and elastomeric bearings, also beginning in the mid 1980s.

Early work in New Zealand is described in Blakeley et al. (1979), Buckle and Mayes (1990), Meggett (1978), Robinson (1982) and Skinner et al. (1975, 1976, 1993). Important early papers and reports by Kelly and his coworkers include Aiken et al. (1989, 1990), Chalhoub and Kelly (1988, 1990), Eidinger and Kelly (1978), Griffith et al. (1988a, 1988b), Kelly (1993), Kelly and Hodder (1981, 1982), Kelly et al. (1977, 1980), Naeim and Kelly (1999) and Pan and Kelly (1985). Important early papers and reports by Mahin and his coworkers include Zayas et al. (1987, 1989, 1990). Important early papers and reports by Constantinou and Reinhorn include Constantinou et al. (1990a, 1990b, 1992), Makris and Constantinou (1991), Mohka et al. (1988, 1990, 1991a, 1991b), Nagarajaiah et al. (1989), Tsopelas and Constantinou (1994, 1997), and Tsopelas et al. (1994, 1996a, 1996b, 1997).

Seismic isolation research, nuclear

There was considerable interest in the United States, Japan and Europe in the late 1980s and early 1990s on the use of seismic isolation to protect nuclear facilities from the effects of extreme earthquake shaking. The US Department of Energy funded a series of studies related to the isolation of advanced reactors. Important studies on the isolation of advanced reactors, which focused on the use of elastomeric bearings, include those reported in Aiken et al. (1989, 1990, 2002), Kelly (1991a), Kulak and Hughes (1991), Tajirian (1992). Tajirian and Abrahamson (1991), Tajirian and Patel (1993), and Tajirian et al. (1989, 1990a, 1990b). Studies in Japan also focused on the use of elastomeric bearings, with results published in numerous papers in SMiRT proceedings. In Europe, isolation of fast breeder reactors was studied and a draft standard was prepared (Forni and Martelli 1995).

Codes and standards, non-nuclear

In the United States, it was recognized that an absence of codes and standards related to the analysis and design of seismic isolation systems would stymie the use of the technology. The Structural Engineers Association of Northern California drafted requirements for analysis and design of seismic isolation systems for buildings in 1986 (SEAONC 1986). The SEAONC Tentative Requirements were followed by the publication of analysis and design provisions for seismic isolation systems in the NEHRP Recommended Provisions (BSSC 1995, 1997, 2001), which were then adopted into ASCE/SEI Standard 7 (ASCE 2002). Other important seismic-isolation-related codes and standards in the United States were FEMA 273 and 274 (FEMA 1997a, 1997b) for existing buildings and the AASHTO Guide Specification

(AASHTO 1999) for bridges. Emphasis in these early codes and standards was placed on equivalent linear methods of analysis because practitioners were unfamiliar with nonlinear dynamic analysis. Best-estimate mechanical properties for isolators were assumed for response-spectrum analysis. The nonlinear force-displacement relationship of the isolation system was replaced by secant stiffness to maximum expected horizontal displacement and the corresponding value of equivalent viscous damping.

European standards were published in the early 2000s that addressed the seismic isolation of buildings (EN 1998-1, CEN 2004) and bridges (EN 1998-2, CEN 2005). These standards were similar in many regards to the corresponding documents in the United States. EN 15129 (CEN 2009), *Anti-seismic devices*, was published in 2009; this standard specifies design and testing requirements and design rules for isolation and damping devices.

Codes and standards, nuclear

ASCE/SEI Standard 4-98 (ASCE 1998), *Seismic analysis of safety-related nuclear structures and commentary*, included mandatory language and commentary for seismically isolated nuclear structures. The text was brief but addressed modeling of isolators and different analysis methods. The provisions and commentary were much less detailed than that provided in US codes and standards for isolated, non-nuclear structures. Variation in the stiffness of the isolation system was addressed using lower bound, best-estimate, and upper bound mechanical properties: identical in concept to the procedures used for the equivalent linear characterization of (nonlinear) soil for soil-structure-interaction analysis.

The Japan Electric Association (JEA) JEAG 4614-2000 (JEA 2000), *Technical guidelines on seismic base isolation systems for structural safety and design of nuclear power plants*, most directly applied to nuclear facilities isolated with elastomeric bearings and associated energy dissipation devices but accepted other types of isolators provided performance specifications were met. Per Kammerer et al. (2018), JEAG 4614-2000 addressed a) classification of seismic isolated nuclear power facilities, b) seismic isolation design and evaluation methodology, c) load combinations and required margins of safety, d) performance requirements for seismic isolation bearings and damping devices, e) design requirements for secondary systems, and f) quality control and maintenance requirements for seismic isolation hardware.

Property modification factors, non-nuclear

It was recognized in the early 1990s, based on experiments and early applications of elastomeric and sliding isolation systems in the United States, that the mechanical properties of seismic isolators would likely differ from the values assumed in a design. Property modification factors were introduced to address variations in mechanical properties from target values for both types of isolator. These factors allowed ranges on mechanical properties to be addressed in a project-specific design. Constantinou and Quarshie (1998), Constantinou et al. (1999), Morgan et al. (2001), Thompson et al. (2000), and Warn and Whittaker (2006a, 2006b) document early work on this subject. The 1999 AASHTO Guide Specification (AASHTO 1999) was the first US standard to implement property modification factors in design of isolation systems.

APPLICATIONS OF SEISMIC ISOLATION TO NUCLEAR FACILITIES

There are six operating, seismically isolated, nuclear power plants in the world. All six are pressurized water reactors (PWR), all were constructed in the late 1970s, and all utilize rubber bearings that are square in plan with polychloroprene as the elastomer. (The use of this synthetic rubber represents a significant difference between United States and European practice. Polychloroprene is not used for seismic isolation bearings in the United States because of concerns regarding the long-term stiffening of the elastomer.) Four isolated PWRs are located at the Cruas-Meysse site in France and two are located at the Koeberg site in South Africa. Kammerer et al. (2018), Labbe (2010), Malushte and Whittaker (2005), Moussallam et al. (2013) and AFCEN (2015) describe different aspects of the construction, including the design bases for the isolated buildings.

The Tokamak (ITER) fusion reactor and the Jules Horowitz research reactor, both under construction in Cadarache, France at the time of this writing, will be isolated with polychloroprene bearings that were fabricated with the mechanical characteristics and manufacturing processes adopted in the 1970s for the isolation systems at the Cruas-Meysse and Koeberg sites. See AFCEN (2015) for details. The procurement and design of the seismic isolators for the ITER project are described in Slee et al. (2013) and Syed et al. (2011), respectively.

Other safety-related nuclear facilities have been seismically isolated, in France and Switzerland. Three spent fuel storage pools at La Hague are isolated with the same type of bearing used at Cruas-Meysse. The Georges Besse II uranium enrichment facility at Tricastin, France is isolated with 500-mm diameter elastomeric bearings. AFCEN (2015) presents information on these projects. The spent fuel pool at the Goesgen nuclear power plant in Switzerland, and a number of diesel generators have been isolated in three dimensions using the spring-damper system introduced previously.

Non-safety-related emergency operations buildings have been isolated at the sites of some nuclear power plants in Japan, in response to changes in Japanese regulations and the 2007 earthquake that impacted the Kashiwazaki-Kariwa nuclear power plant (Kammerer et al. 2018). The Japanese applications utilize elastomeric bearings.

RECENT DEVELOPMENTS AND BEST PRACTICE

United States

MCEER developed an advanced methodology for seismic probabilistic risk assessment of seismically isolated nuclear structures, taking advantage of existing methods of systems analysis (involving event trees and fault trees), modern seismic hazard analysis, modern methods of selecting and scaling earthquake ground motions, nonlinear dynamic analysis of soil-isolation-structure systems, and fragility functions for structures, systems and components based on local demands (e.g., in-structure floor spectral demand, story drift, peak floor velocity), and Monte Carlo calculations that generated conditional probabilities of unacceptable performance at user-specified intensities of shaking. This methodology, which involves analysis at up to eight intensities of earthquake shaking, spanning a range of shaking associated with no damage (a fraction of design basis earthquake shaking) through near-complete damage (multiples of design basis earthquake shaking), accommodated the highly nonlinear behaviour of the isolators proposed for use in nuclear structures in the United States (namely lead-rubber and FP bearings), and through the use of nonlinear dynamic analysis, nonlinear behaviour in the supporting soil and isolated superstructure. Huang et al. (2008, 2011b, 2011c) document the methodology and provide an example application.

MCEER supported a short-term research project that provided some of the key technical underpinnings for the seismic design criteria for isolated nuclear facilities that are presented in Chapter 12 of ASCE/SEI

4-16 (ASCE 2017). Key outcomes from the project, which are described in Huang et al. (2009, 2013) address the response of base-isolated nuclear facilities in the Department of Energy complex to design basis and beyond design basis earthquake shaking, identify the relative importance of variability in the mechanical properties of the seismic isolation system and in the earthquake ground motions used for dynamic analysis, and describe the effect on isolator displacement response of different descriptions of the input ground motions.

Building on the PEER methodology for performance-based earthquake engineering of buildings, Morgan and Mahin (2010, 2011) describe how multiple seismic performance objectives can be achieved with the seismic isolation bearings, with a focus on the triple FP bearing, introduced previously. Morgan and McDonald (2013) extended the study on buildings to illustrate how seismic isolation could be used to achieve a uniform level of risk for standardized plant designs.

The United States Nuclear Regulatory Commission (NRC) funded a multi-year research project on the application of seismic isolation to NPPs in the United States, involving research staff at the Lawrence Berkeley National Laboratory and at MCEER at the University at Buffalo. These studies addressed elastomeric and sliding (FP) bearings and included a) writing of a seismic isolation NUREG, two MCEER reports, and two NUREG Contractor Reports, b) risk-based studies to develop analysis and design criteria to meet the seismic performance goals of both ASCE 43 (ASCE 2005) and the NRC, including the provision of a stop, c) execution of experiments on elastomeric bearings under combined tension and shear, d) development of advanced, verified and validated numerical models of elastomeric isolation bearings capable of capturing isolator response under extreme loadings, e) implementation of the advanced isolator models in the open-source finite element codes OpenSees and MOOSE, and the commercial finite element codes LS-DYNA and ABAQUS, f) the development of an advanced model for sliding bearings capable of tracking changes in the coefficient of friction at the sliding information as a function of pressure, velocity and temperature, g) calculations of the seismic risk associated with the failure of an isolation system, for eight sites of nuclear facilities across the United States, for design per ASCE 4-16 and the seismic isolation NUREG, with and without a displacement restraint (stop), h) developing recommendations for selection and scaling of ground motions, with considerations of uniform hazard spectra, conditional mean spectra, and conditional spectra, and j) characterizing the effect of aircraft impact on a seismically isolated NPP in terms of in-structure spectra at selected points within a containment vessel. Kumar and Whittaker (2015, 2017a, 2018) and Kumar et al. (2013b, 2013c, 2014, 2015a, 2015b, 2015c, 2015d, 2015e, 2015f, 2017a, 2017b, 2017c) present results of the research project. More publications are planned.

The US Department of Energy (DOE) has funded studies in the past few years on the seismic isolation of nuclear facilities, with consideration of nonlinear soil-structure-interaction analysis. The impediments to the use of seismic isolation, in terms of regulatory gaps and inadequately characterized benefits and costs have been identified. Action plans to address and fill the gaps have been developed (e.g., Kammerer et al. 2016a, 2016b). A preliminary study to establish the costs and benefits of seismic isolation, measured using risk and overnight capital cost (of construction), has been completed and results have been published (Bolisetti et al. 2016; Yu et al. 2018). The isolation of deeply embedded advanced reactors and of systems and components inside advanced reactors, and analysis of isolated fluid-structure systems are all the subject of on-going research between DOE and MCEER.

The American Society of Civil Engineers published two standards related to the analysis and design of safety-related nuclear structures. Standard ASCE/SEI 4-98 (ASCE 1998) included mandatory language and commentary, albeit insufficient, that could be used to analyse a seismically isolated nuclear facility.

Standard ASCE/SEI 43-05 (ASCE 2005) addresses design of nuclear facilities and provides target performance goals based on a user-specified seismic design category. Standard ASCE/SEI 4 was substantially revised and published in early 2017 (as ASCE/SEI 4-16), and includes a chapter on the analysis and design of a seismic isolation system for a nuclear facility. The mandatory language is risk based, with requirements that will achieve the target performance goals of ASCE/SEI 43-05, namely, a 1% maximum probability of unacceptable performance at design basis shaking, and a 10% maximum probability of unacceptable performance at 150% design basis shaking.

Table 1 presents the performance goals for a seismically isolated nuclear facility designed in accordance with ASCE/SEI 4-16; in this table, DBE and BDBE identify design basis earthquake shaking and beyond design basis earthquake shaking, respectively. The technical basis assumes the use of one of three types of isolator: low-damping natural rubber bearing, lead-rubber bearing (using natural rubber as the elastomer), or the Friction Pendulum sliding bearing.

	DBE	BDBE
Use	Response spectrum per Chapter 2. Production testing of isolators. Design loads for isolated superstructure. In-structure response spectra (ISRS).	150% of DBE. Prototype testing of isolators. Selecting moat width [or clearance to stop (CS)].
Isolation system		
Isolation system displacement	Mean and 80th percentile isolation system displacements.	90th percentile isolation system displacement.[b]
Performance	No damage to the isolation system for DBE shaking.	Greater than 90% probability of the isolation system surviving BDBE shaking without loss of gravity-load capacity.
Acceptance criteria	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.	Prototype testing of a sufficient[c] number of isolators for the CS displacement and the corresponding axial force. Isolator damage is acceptable but load-carrying capacity is maintained.
Superstructure		
Performance	Conform to consensus materials standards for 80th percentile demands. Greater than 98% probability that component capacities will not be exceeded. Greater than 98% probability that the superstructure will not contact the moat.[a]	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.
Other SSCs		
Performance	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.	Greater than 90% probability that component capacities will not be exceeded.
Umbilical lines	–	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.
Stop or moat	–	CS or moat width equal to or greater than the 90th percentile displacement. Damage to the moat is acceptable in the event of contact.

[a]Can be achieved by satisfying the requirement for BDBE shaking.
[b]90th percentile BDBE displacements may be calculated by multiplying the mean DBE displacement by a factor of 3.
[c]The number of prototype isolators to be tested shall be sufficient to provide the required 90+% confidence.

Table 1. Performance goals for a seismically isolated DOE nuclear facility (ASCE 2017)

A displacement restraint (stop) is needed to achieve the target performance goals, where the stop will generally surround the nuclear facility (see Figure 3) and the moat wall can serve as the restraint on isolator horizontal displacement. The horizontal gap between the isolated superstructure and the stop (moat wall) shall be no less that the 90th-percentile displacement for beyond design basis shaking (taken for DOE facilities as 150% design basis shaking). Soil-structure interaction is addressed explicitly, with three approaches provided, namely, 1) a fully coupled time domain (nonlinear) analysis, 2) an equivalent linear frequency domain solution (for low-damping natural rubber bearings only), and 3) a multi-step method, which uses traditional equivalent linear techniques to treat soil-structure interaction, generates seismic isolation design response spectra at the underside of the foundation, generates sets of three-component ground motions consistent with the foundation spectra, and nonlinear response-history analysis of the isolated superstructure using the sets of ground motions. The chapter provides detailed recommendations on the prototype and production testing of isolators. The sequence and cycles of loading required for the prototype testing are drawn from other standards that include provisions for seismic isolation and from Warn and Whittaker (2004, 2006a). Full-scale prototype isolators must be tested simultaneously in shear and axial load: dynamically under lateral loading to achieve a horizontal displacement equal to the clearance to the stop for the maximum and minimum axial forces that can develop at that displacement. All production isolators are tested for mean demands calculated for design basis shaking.

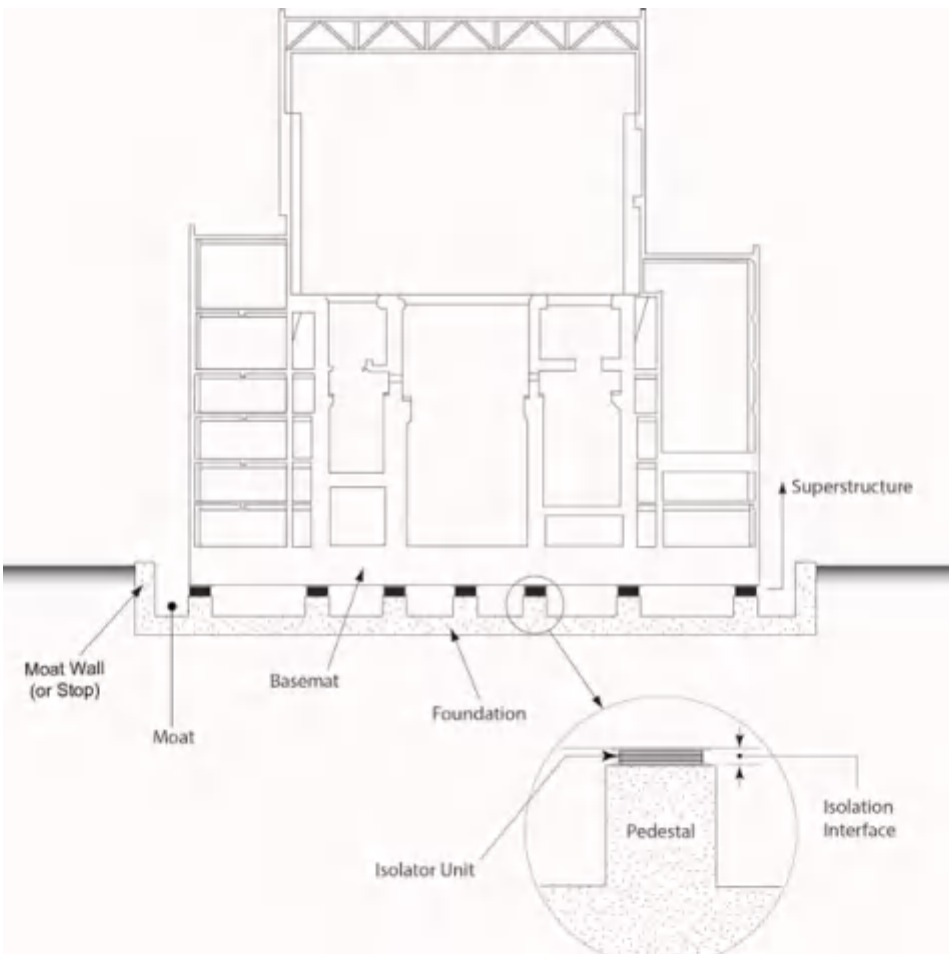


Figure 3. Cross section through an isolated nuclear facility

Standard ASCE 43-05 is being revised at the time of this writing (Abatt et al. 2017) for re-issue in late 2018. Those provisions and commentary in Chapter 12 of ASCE/SEI 4-16 that do not address *analysis* of seismically isolated nuclear facilities, including, substructure and superstructure design, isolator-to-structure connections, and prototype and production isolator testing, will be moved to Chapter 9 of

ASCE/SEI 43-18. The provisions and commentary moved to Chapter 9 of ASCE/SEI 43-18 will then be removed from Chapter 12 of the next version of ASCE/SEI 4.

Europe

The SILER research and development program, which was funded by the European Union, focused on the mitigation of seismic risk to Generation IV liquid metal reactors, which explicit consideration of horizontal seismic isolation and the effects of shaking greater than design basis. SILER considered fast lead reactors (the European Lead Fast Reactor, ELSY) and the so-called Accelerator Driven System (Multi-purpose hYbrid Research Reactor for High-tech Applications, MYRRHA). High damping rubber bearing and LR bearing isolation systems were developed. Experiments were performed to demonstrate isolator adequacy and to show margin over design basis earthquake demands. Components that cross the isolation interface, including steam lines to the turbine building, were designed, detailed and tested. Forni et al. (2015) and the SILER website, www.siler.eu, provide information on the program.

The SILER program continues at this time as part of the Euratom project European Sustainable Nuclear Industrial Initiative (ESNII). Seismic isolation systems using polychloroprene bearings have been developed for the 125 MWe Advanced Lead-cooled Fast Reactor European Demonstrator (ALFRED) and the 600 MWe Advanced Sodium Technological Reactor for Industrial Demonstration (ASTRID). Information on ALFRED and ASTRID is presented in Poggianti et al. (2015) and Vézin et al. (2013).

The French association for nuclear steam system supply equipment construction rules, AFCEN, have developed rules for design of base isolated structures (AFCEN 2016) using elastomeric bearings. The standard provides information on isolator distribution, analysis procedures, isolator modelling, and isolator verification procedures.

Korea

The Korea Atomic Energy Research Institute (KAERI) and Korea Electric Power Corporation (KEPCO) funded research for a five-year period on the seismic isolation of nuclear power plants. Korean practice was substantially advanced in six key subject areas: 1) acceptance criteria for seismically isolated NPPs (including the plant, individual isolators, isolation systems) and tests for isolation bearings, 2) operation of a seismically isolated NPP (including aging characteristics of seismic isolators and in-service inspection of seismic isolators), 3) performance criteria for interface piping systems (including calculation of seismic anchor motions, and modelling, analysis and performance assessment of distribution systems), 4) seismic fragility and risk assessment of isolated NPPs (including fragilities of isolation systems, distribution systems and equipment, and plant-level risk assessment), 5) drafting of seismic design criteria for seismically isolated NPPs (to be published in 2017 by the Korea Electric Power Industry Code), and 6) development of advanced elastomers for seismic isolators and multi-core lead-rubber bearings. The products of this research project are now being published (e.g., Hahm and Kim 2016, Ju et al. 2016, Kim and Kim 2016; Kim et al. 2015a, 2015b, 2016, 2017; Park et al. 2016a, 2016b, Sarebanha et al. 2017).

Japan

The former Japan Nuclear Energy Safety (JNES) organization, now a part of the Nuclear Regulatory Authority of Japan (NRAJ), initiated a program to develop new regulatory guidance for the design of isolated nuclear power plants. The draft JNES guidance on seismic isolation, JNES-22-11-1, *Technical review guidelines for structures with seismic isolation*, was published in English in 2011 (JNES 2011).

The final version was released in 2014 as JNES-RC-2013-1002, *Proposal of technical review guidelines for structures with seismic isolation* (JNES 2014). The 2014 guidelines discuss regulatory positions and their technical bases, and identify relevant regulatory review elements, but do not specify acceptable types of seismic isolators. The design of vertical isolation systems and the isolation of equipment and floors are discussed. The guidelines are generally based on deterministic approaches. Design of the isolation system can be performed using either a margins approach or seismic probabilistic risk assessment techniques. The JNES guidance provides for margin above design basis shaking for isolator capacity, clearance to adjacent structures, and on capacity for umbilical piping. No specific margin is identified. Kammerer at al. (2017) provides additional information on JNES-RC-2013-1002.

Russia

The Russian State Corporation is supporting the development of a 3D seismic isolation system for the VVER class of reactors. The proposed isolation system incorporates vertically installed steel springs and viscous dashpots, as introduced previously. A Russian standard on the seismic isolation of nuclear power plants is being developed.

FUTURE NEEDS

Much research and development has been accomplished in the past decade. In the United States, tools, numerical models, and techniques have been developed and deployed to enable the horizontal seismic isolation of surface-mounted or near-surface-mounted nuclear facilities. Importantly, for applications in the United States, risk-based guidance on the analysis, design and performance assessment of seismically isolated nuclear facilities has been prepared and distributed in the form of ASCE/SEI 4-16, the seismic isolation NUREG (Kammerer et al. 2018), two MCEER reports (Kumar et al. 2015e, 2015f) that are being updated and republished as NUREG/CRs, and numerous journal and conference papers (Huang et al. 2008, 2009, 2010, 2011a, 2011b, 2011c, 2013), Kumar et al. 2013b, 2013c, 2014, 2015a, 2015b, 2015c, 2015d, 2015e, 2015f, 2017a, 2017b, Kumar and Whittaker 2015).These peer-reviewed documents provide a robust technical basis for the isolation of nuclear facilities, including surface and near-surface-mounted nuclear buildings, including large light water reactors of the type being constructed at this time in the United States. Not yet completely addressed and/or characterized are the following topics related to the use of protective systems in nuclear structures, where protective systems include seismic isolators and energy dissipation devices:

- Two-dimensional seismic isolators and isolation systems for systems and components in nuclear facilities, surface mounted and deeply embedded
- Three-dimensional seismic isolators and isolation systems for components and sub-systems in nuclear facilities
- Three-dimensional seismic isolators and isolation systems for buildings
- One-dimensional supplemental damping (energy dissipation) devices for protection of components and systems in isolated and conventionally founded nuclear facilities
- Isolation of advanced reactors: facilities with geometry that is fundamentally different from the reactors in the existing fleet in the United States
- Potential nonlinear demands on structures, systems and components for beyond design basis shaking in isolated power plants, identified by Politopoulos and Sollogoub (2005) and more recently by Tsiavos et al. (2016) for linear bearings.
- Development and deployment of verified and validated models of components of nonlinear soil-structure-fluid systems (extending the current development of MOOSE [mooseframework.org] at

the Idaho National Laboratory)

- Isolation of advanced reactors with explicit considerations of fluid-structure interaction and soil-structure interaction (extending the studies of Christovasilis and Whittaker 2008)
- Accurate characterization of the costs of systems and components in advanced reactors as a function of the intensity of the horizontal and vertical inputs at points of attachment
- Accurate characterization of the costs and benefits associated with isolation of advanced reactors, and components and systems therein (extending the studies of Bolisetti et al. 2016, and Yu et al. 2018)
- Assessment of isolated nuclear facilities for non-seismic extreme natural events and beyond-design basis aircraft impact (extending the studies of Kulak and Yoo (2003), Keldrauk et al. (2013), and Kumar and Whittaker (2018))
- Effect of radiation exposure on the mechanical properties of elastomeric and sliding isolation bearings and energy dissipation devices (such as fluid viscous dampers).

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