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EQUIPMENT-LEVEL SEISMIC PROTECTIVE SYSTEMS FOR ADVANCED NUCLEAR REACTORS

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Abstract

The seismic load case is a key contributor to the overnight capital cost (OCC) and levelized cost of energy (LCOE) of conventionally constructed nuclear power plants (NPPs). Because design basis earthquake (DBE) shaking is location dependent, no two NPPs at different sites are identical, namely, each NPP is a First-of-a-Kind (FoaK). The seismic isolation of reactor buildings is one pathway to Nth-of-a-Kind (NoaK) construction and possible drastic reductions in both OCC and LCOE. Some proposed advanced reactor buildings are deeply embedded, which may make the cost of building isolation prohibitive. For such buildings, horizontal isolation of individual pieces of safety-class equipment may be a practical and cost-effective solution, and enable NoaK equipment. Surface-mounted advanced reactors could also employ equipment-level seismic protective systems. A MEITNER project, funded by the Advanced Research Projects Agency-Energy, is now underway to provide the technical basis for the implementation of equipment-based seismic protective systems, with the overarching goal of driving down the OCC and LCOE of advanced reactors.

This paper presents a pathway to NoaK equipment using equipment-level seismic protective systems. A paradigm shift in design practice is proposed, wherein a piece of safety-class equipment is designed for operational loadings only, its resultant seismic capacity (design space) is established, and that capacity is used to drive the choice of a seismic protective (isolation) system. Such a process focuses on reducing or eliminating the impact of the seismic load case on the functionality and cost of the safety-class asset.

The process is demonstrated using a *generic* high temperature gas reactor (HTGR) building equipped with three safety-class assets: a reactor vessel, a steam generator, and a control rod drive mechanism housing. Designs for the reactor building and the safety-class equipment were developed per ASCE/SEI Standards 4 and 43, ACI 349, and the ASME Boiler and Pressure Vessel code. Numerical models of the reactor building and the safety-class equipment were developed and analyzed for ground motions consistent with DBE shaking at the site of the Idaho National Laboratory (INL).

The concept of equipment *design space* is proposed, which describes the seismic capacity of a piece of equipment or an assembly of equipment, measured in terms of a user-specified combination of stresses, accelerations, velocities, deformations, and displacements. Hypothetical design spaces are proposed for the equipment in the HTGR building. Four seismic protective systems, specific to the building and the INL site, are investigated to identify solutions that fall within the design spaces. One of the four isolation systems was optimal for the chosen building, site, and equipment. Because the impact of the seismic load case is eliminated with the use of the optimal isolation system, equipment designed for operational performance only could be used. Identical equipment could be used at a different site, with the only possible change being an alternate isolation system: the pathway to NoaK equipment.

Keywords: equipment isolation, advanced reactors, design space, Nth-of-a-Kind, First-of-a-Kind

1. Introduction

One of the major impediments to the construction of new nuclear power plants (NPPs) is the high projected overnight capital cost (OCC) per MWe and levelized cost of energy (LCOE). The seismic load case is a key driver of high OCC. At this time, every new build NPP is by-and-large a First-of-a-Kind (FoaK) design because no two plants are located at sites of identical local geology and seismic hazard. Site-specific seismic analysis, design, qualification, and regulatory review will generally be required if conventional construction is employed, although near-identical structures, systems and components could possibly be used across multiple sites if sufficient conservatism (resulting in increased OCC and LCOE) is introduced into the baseline design. There is no pathway to Nth-of-a-Kind (NoaK) construction with the legacy procedures for design and construction of NPPs.

Seismic isolation is a mature technology that could be deployed to mitigate the effects of earthquake shaking in advanced reactors. The technology could be implemented at: 1) the building-level, where seismic isolators (or bearings) are installed beneath the basemat of a reactor building, or 2) at the equipment-level, where an individual piece (or an assembly) of safety-class equipment is isolated at their points of attachment to the building. The first solution could enable NoaK construction of nuclear plants. The second solution could enable NoaK equipment, and that is the focus of this paper.

The US Department of Energy and the Nuclear Regulatory Commission (NRC) has funded a number of research projects over the past decade to develop standards and guidance for the application of seismic isolation to reactor buildings. Research funded by these agencies led to the addition of chapters specific to seismic isolation in ASCE/SEI Standards 4-16 [1] and 43-19 [2]. The NRC-funded research contributed to three contractor reports: NUREG/CR-7253 [3], NUREG/CR-7254 [4], and NUREG/CR-7255 [5]. Journal articles, conference papers, and MCEER technical reports were published to support and complement these publications, with most identified in Whittaker *et al*. (2018) [6]. The Electric Power Research Institute is currently funding a study to characterize the financial impact of the seismic load case on construction of new NPPs and the cost savings made possible by the use of base isolation [7, 8]. All of these studies have focused on isolation of reactor buildings.

Some proposed advanced reactor buildings are deeply embedded and the cost to implement building isolation may be prohibitive because of the required increase in excavation and construction of a permanent retaining wall around the isolated building. Equipment-level isolation is a viable strategy to reduce the impact of the seismic load case in such a case. Equipment-level isolation could also be deployed in surface-mounted buildings, and vertical isolation of equipment in a horizontally isolated reactor building is a practical pathway to 3D seismic protection. The Advanced Research Projects Agency—Energy (ARPA-E), a US government agency that supports research and development of advanced energy technologies, is funding a MEITNER project, with the goal of operationalizing equipment-based seismic protective systems in advanced reactors and consequently reducing their OCC and LCOE.

One of the objectives of this MEITNER project is to enable a paradigm shift in the engineering and fabrication of safety-class equipment in advanced reactors by operationalizing seismic *design spaces*. Every piece of mechanical equipment designed per the ASME Boiler and Pressure Vessel code [9] for operational loadings only will have some capacity to resist the effects of earthquake shaking. Herein, a design space for a piece of equipment or an assembly of equipment is assumed to be a user-specified combination of limiting stresses, accelerations, velocities, deformations, and displacements. A trial design space could be established by seismic analysis of a piece of equipment, or an assembly of equipment, designed for operational loadings only (i.e., no seismic load case) and identify the intensity of shaking that the equipment could sustain without modifications to its design. Such studies could also identify thresholds of shaking associated with fundamental changes in design and significant increases in fabrication cost. Design spaces would vary by reactor technology and equipment type. Once a design space for a piece of equipment or an assembly of equipment is established, a seismic protective system could be deployed to limit stresses, accelerations, velocities, deformations, and displacements to the limits of the design space, allowing standardization and a pathway to NoaK equipment, as noted previously.

The MEITNER project is using two advanced reactors as test beds: a molten chloride fast reactor and a high temperature gas reactor (HTGR). Only the HTGR is discussed in this paper. Fig. 1 presents a cut-away view of the key components of a HTGR: a reactor vessel (RV) and a steam generator (SG), which are physically connected by a cross-over pipe. Control rod drive mechanisms (CRDM), which serve to control reactivity and scram the reactor in the event of an accident, are located at the head of the RV. The CRDM housings, which guide the insertion and withdrawal of these control rods, are welded to the reactor head. Some of the parameters that could define design spaces for these pieces of equipment are: 1) deformation capacity of the cross-over pipe that will limit the relative movement of the RV and SG, 2) accelerations and displacements of the pebble fuel outlet at the bottom of the RV, 3) horizontal accelerations at the point of attachment and top of the CRDM housings, which will affect the functionality of the control rods in the event of scram under earthquake shaking, and 4) accelerations and displacements at the top and bottom of the RV and SG, which will affect the stresses in the vessel walls and the response of the internals.

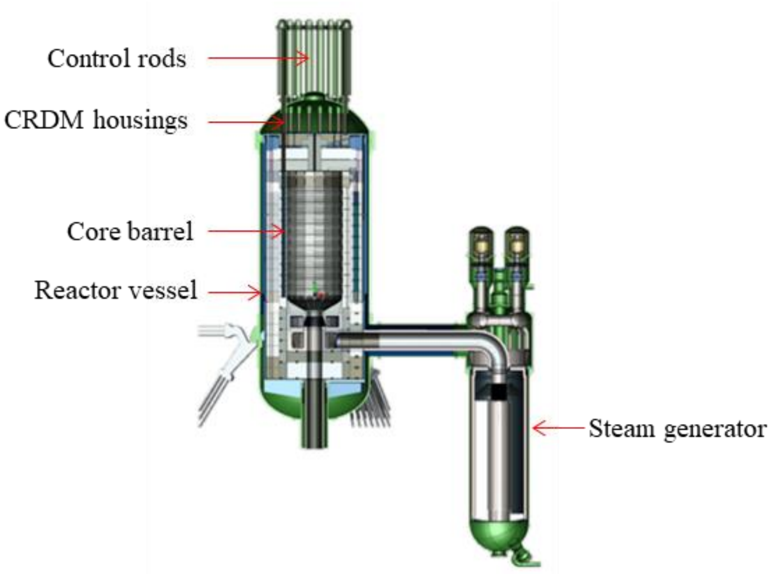


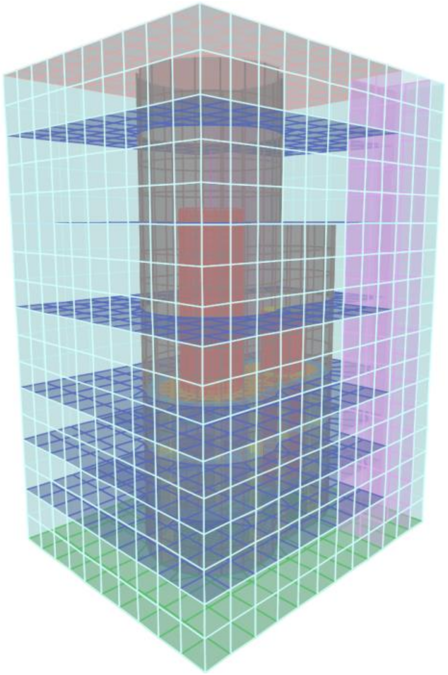
Fig. 1 Cut-away view of equipment in HTGR (courtesy of X-energy)

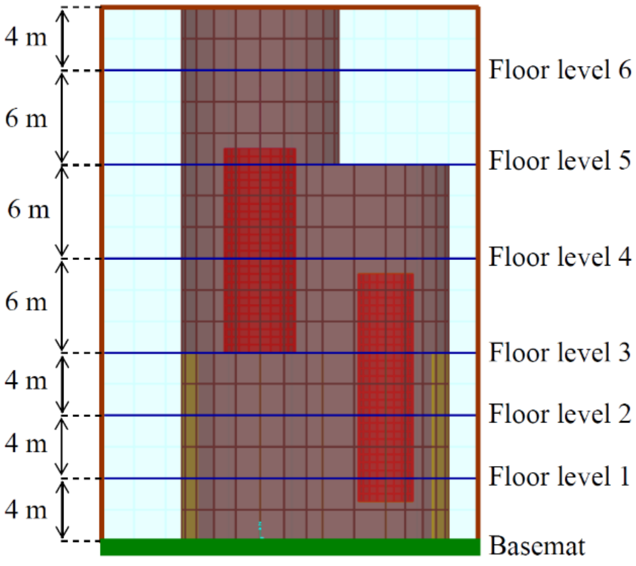
The remainder of this paper illustrates a process for designing and selecting seismic protective systems for the safety-class equipment in a generic HTGR. The process involves finite element modeling, identification of plausible isolation solutions, non-linear dynamic analysis, definition of design spaces, and identification of an optimal isolation system.

2. Reactor building and safety-class equipment

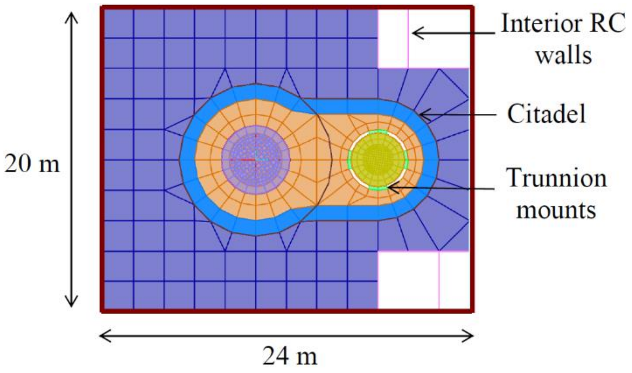
2.1. Introduction

The *generic* HTGR building considered herein is a 34 m high structure with overall plan dimensions of 24 m × 20 m, and perimeter walls of reinforced concrete (RC). The reactor building was assumed to be sited within the boundaries of the Idaho National Laboratory (INL). The building has two major compartments (citadels), one housing a RV and extending from the basemat to the roof, and the other housing a steam generator and extending up to the floor level 5, 24 m above the basemat. The RC walls of the citadels are 1 m thick. The perimeter and the citadel RC walls are the lateral force resisting system. The RV and SG are supported on a 2-m thick RC floor slab at level 3. All other RC floor slabs, including the roof are 0.5 m thick. Fig. 2 presents isometric, elevation, and plan views of the reactor building, showing the RV and SG.





b) elevation view



a) isometric view

c) plan view (floor level 3)

Fig. 2 Views of the generic HTGR building

Fig. 3 identifies the pieces of safety-class equipment in the HTGR building considered in this study. The RV is 4.5 m in diameter, 13 m tall and includes internals weighing approximately 350 tons. The 4 m tall tubular CRDM housing is welded to the reactor head and has an outside diameter of 260 mm and a wall thickness of 25 mm. (The reactor head supports many such housings but only one unit is considered here.) The SG is housed inside the smaller citadel, and is 14.5 m tall and 3.5 m in diameter. The SG is also supported at the level of the RV (floor level 3), with projections of 5 m and 9.5 m, above and below the floor, respectively. Four trunnion mounts are extended from the SG (see Fig. 2c) to support it on the adjacent floor slab. The SG includes internals weighing approximately 100 tons. The cross-over pipe connecting the RV and SG is not modeled here because both the vessels are attached to the level 3 floor slab.

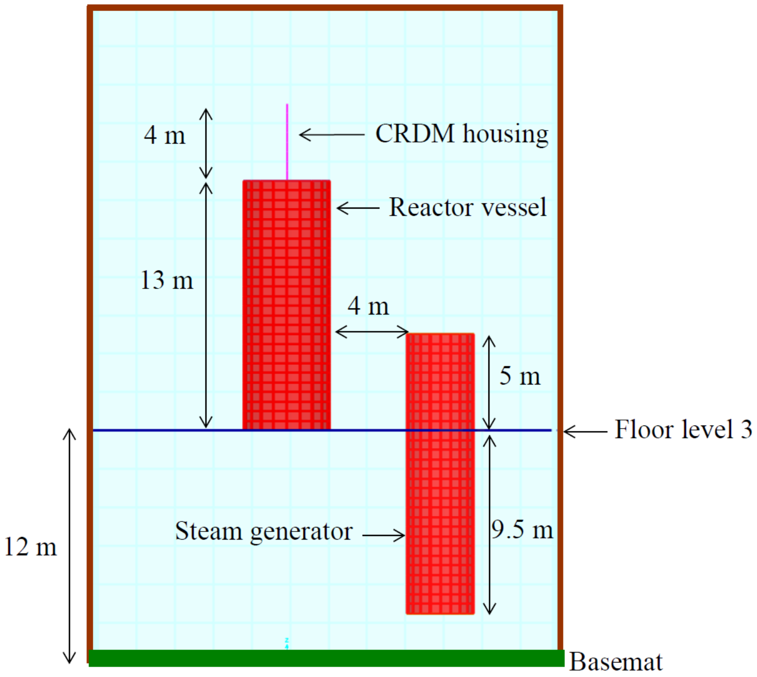


Fig.3 Safety-class equipment in the HTGR building

2.2. Numerical modeling

Numerical models for the reactor building and its safety-class equipment were developed in the commercial finite element program SAP 2000 [10]. The exterior and interior RC walls, floor and roof slabs, citadel walls, and the basemat were modeled using four-node shell elements. The concrete was assumed to be uncracked, to have a density of 2400 kg/m^3, and a uniaxial compressive strength of 27.5 MPa (4000 psi). The base of the building was assumed to be fixed and soil-structure interaction was ignored for the analysis.

The pressure vessels (RV and SG) were modeled using four-node shell elements, and included in the numerical model of the reactor building. The RV and SG were assumed to be constructed from SA 508 and SA 516 alloy steel, respectively. The mechanical properties for these alloy steels were consistent with the assumed operating temperature of 285°C. The CRDM housing was modeled using a beam element with an appropriate cross-section, and assumed to be fabricated from SA 508 alloy steel with a Young's modulus of 200 GPa. The density of the steel components was assumed to be 7850 kg/m^3. The mass of the RV and the SG internals were distributed uniformly along the height of the vessels.

2.3. Design of the reactor building and safety-class equipment

Trial designs were developed for the building framing using ASCE/SEI 4-16 and 43-19, and ACI 349-13 [11]. Seismic loads were assumed to govern the design of the building framing. The required thicknesses of the RC walls were established by response-spectrum analysis of the numerical model of the building using a Regulatory Guide (RG) 1.60 [12] spectrum, anchored to a peak ground acceleration of 0.3 g. In-plane shear stresses in the walls were compared with the limits of ACI-349 and thicknesses were revised until the solution converged. The floor and roof slabs were sized to support gravity loads, with a margin for earthquake shaking effects.

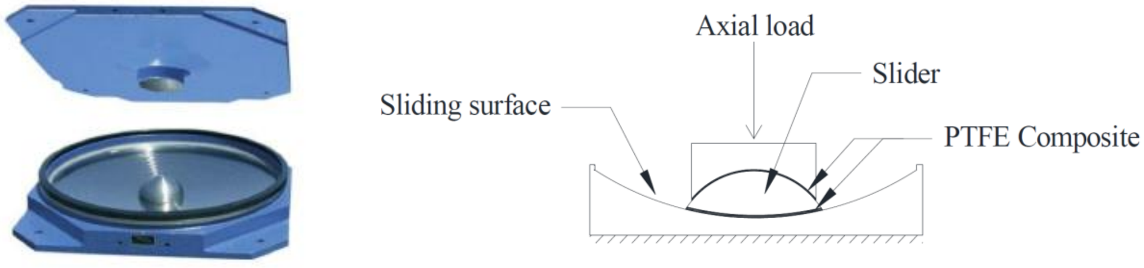
The walls of the RV and SG pressure vessels were sized initially for operational loadings only, namely, gravity and internal operating pressure (70 bars, 7 MPa), for allowable stress intensities per Section III, Division V of the ASME Boiler and Pressure Vessel code [9]. The minimum wall thickness of the pressure vessels, for operational loadings only, were 85 mm (RV) and 104 mm (SG).

The translation frequencies of the final version of the fixed-base building were between 6 and 7 Hz. The first mode frequencies of the RV, SG, and the CRDM housing were 8 Hz, 12 Hz, and 14 Hz, respectively.

3. Design of isolation systems

3.1. Introduction

Single concave Friction Pendulum (FP) bearings were used for the horizontal (2D) isolation of the safety-class equipment. The single FP bearing consists of an articulated slider coated with high load-low friction composite, a sliding surface, and a housing plate. Fig. 4 presents information on the FP bearing. The behavior of an FP bearing is governed by two parameters: 1) coefficient of friction at the sliding interface, and 2) radius of curvature of the sliding surface. Candidate isolation systems were designed per the provisions of the Chapter 12 of ASCE/SEI 4-16. The lead-rubber (LR) bearing [3, 5] is a viable alternative to the FP bearing but only one isolator type was considered in the study reported in this paper. (The outcomes are independent of the bearings used: FP or LR.)



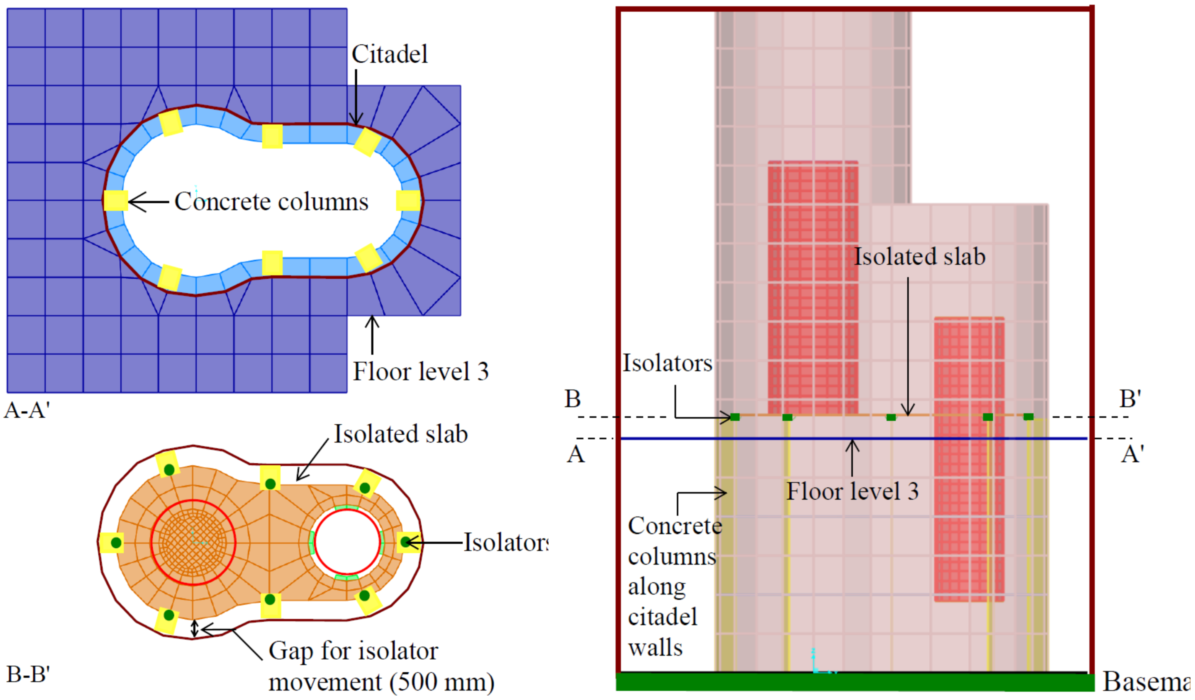
a) components b) sectional view

Fig. 4 Single concave Friction Pendulum™ bearing [4]

3.2. Isolation of the safety-class equipment

Herein, the equipment assembly (i.e., RV, SG, and CRDM housing) is isolated. The RV and SG are supported on a 2 m thick slab (shown in orange, section B-B’, Fig. 5a) at floor level 3. To support the isolators, eight reinforced concrete columns were extended from the basemat along the walls of the citadels, as shown in Fig. 5b. (Other solutions, including corbels attached to the citadel walls, are feasible.) An FP bearing was installed atop each of these columns and beneath the floor slab supporting the RV and SG.

The FP bearings were modelled using two-node link type element and were assigned the ‘*friction isolator*’ material available in SAP2000. In the fixed-base building, the slab supporting the RV and SG and floor level 3 (shown in blue, section A-A’, Fig. 5a) are continuous (see Fig. 2c). In the building in which the equipment is isolated, the slab supporting the equipment is raised above the floor level 3 to enable installation of the bearings. A 500 mm gap, shown in Fig. 5a, is provided between the isolated slab and the citadel walls to enable unrestricted horizontal movement of the isolators during earthquake shaking.



a) plan views b) elevation view

Fig. 5 Isolation of the safety-class equipment in the HTGR building

3.3. Isolation system properties

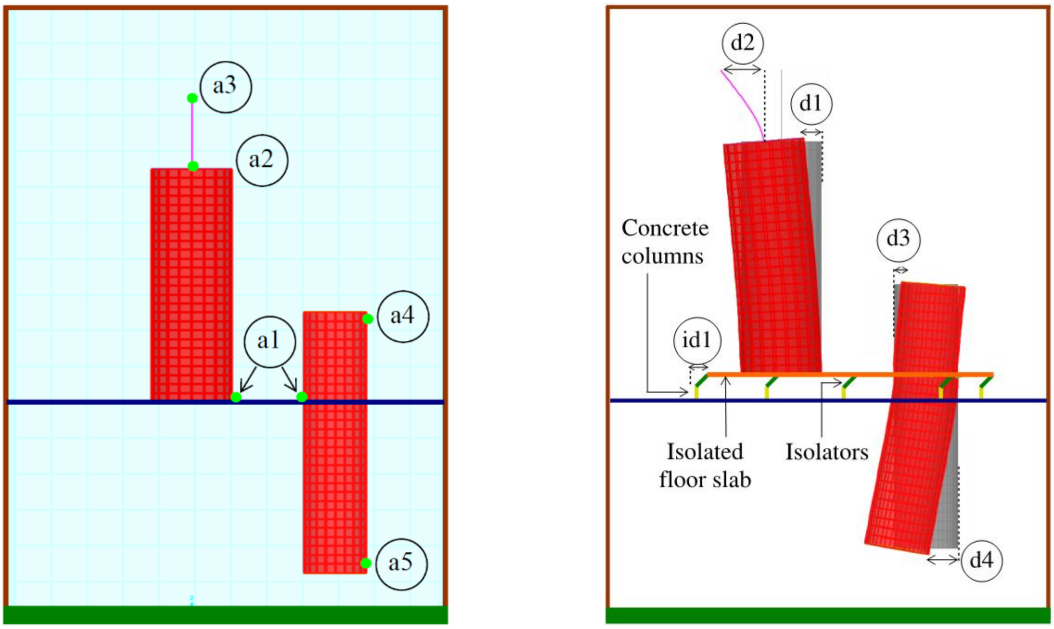
Isolation of equipment will reduce accelerations and deformations but the displacements across the height of the isolators must be accommodated by any umbilical lines that cross the isolation interface. Herein, the design space is defined by accelerations in the equipment and displacement across the isolation interface. Four isolation systems were analyzed to identify the optimal solution and to demonstrate how altering the mechanical properties of the isolators could result in different combinations of acceleration and displacement. The four isolation systems are defined by number [coefficient of friction, sliding surface radius, sliding period]: 1 [0.09, 1000 mm, 2 sec], 2 [0.07, 2230 mm, 3 sec], 3 [0.05, 4000 mm, 4 sec], and 4 [0.03, 6210 mm, 5 sec].

4. Response-history analysis

Design basis earthquake (DBE) at the INL site was characterized by Yu *et al*., (2018) [13] in terms of an acceleration response spectrum corresponding to a mean annual frequency of exceedance of 1×10^{-4} (a 10,000-year return period). The Yu study developed thirty sets of ground motions consistent with the target spectrum and were used for the analysis here. The seismic hazard characterization and selection and scaling of ground motions of the Yu study are not repeated here. Vertical earthquake shaking was not considered.

Numerical models were developed for two building configurations: 1) fixed-base, and 2) equipment-isolated (EI). The EI building was analyzed for the four isolation systems described in Section 3.3. The fast-nonlinear analysis algorithm in SAP2000 was employed for the nonlinear response-history analysis. This algorithm uses Ritz modes for modal decomposition and the first 150 modes, which recovered 99% and 90% of the mass in the horizontal and the vertical directions, respectively, were used for the analysis. A modal damping ratio of 4% was assigned to these 150 modes for the fixed-base building. In the EI building, the isolators provide hysteretic damping; to avoid overdamping the isolation system, 1% damping was assigned to the isolated modes and 4% damping was assigned to all other modes.

Horizontal accelerations were monitored at the points of attachment of the equipment and representative locations on the internals. These points are identified using solid green circles in Fig. 6a: #a1- point of attachment of the RV and SG; #a2 - top of the RV; #a3 - the top of the CRDM housing; #a4 - top of the SG; #a5 - bottom of the SG. The horizontal accelerations #a1 through #a5 were calculated at the 80th percentile per ASCE/SEI 4-16 by statistical analysis of the peak accelerations from the 30 response-history analyses. The accelerations on the internals (#a2, #a4, and #a5) and at the upper end of the CRDM housing (#a3) were increased by 25% because the assumed 4% modal damping is too high for the equipment for which 2% (or less) would be appropriate. (The modes involving significant responses of the equipment are coupled with the building modes and it was not possible to separately assign damping to the reinforced concrete and the equipment.)



a) horizontal accelerations b) horizontal displacements

Fig. 6 Response quantities of interest reported in the HTGR building

The displacement across the isolation interface is denoted as #id1 and was also calculated at the 80th percentile. The relative displacements of the equipment with respect to their points of attachment are identified in Fig. 6b: #d1- top of the RV; #d2 - top of the CRDM housing; #d3 - top of the SG; #d4 - bottom of the SG. The relative displacements were also calculated at the 80th percentile and then increased by 25% to account for their 2% or less damping.

5. Results and discussion

5.1. Analysis results

The 80th percentile horizontal accelerations and displacements of Fig. 6 are reported in Table 1. In the fixed-base building, the ground motion is amplified from the basemat to the top of the RV by a factor of 10 (0.3 g to 3.2 g); from the basemat to the top of the CRDM housing by a factor of 25 (0.3 g to 7.7 g); and from the basemat to the bottom of the SG by a factor of 6 (0.3 g to 1.8 g). These accelerations will pose a significant challenge to the design and qualification of the equipment and their internals.

Importantly, these accelerations will trigger significant changes to the vessels and their internals, requiring a bespoke engineering design and substantial increases in cost. By isolating the equipment, the accelerations are drastically reduced for all of the isolation systems considered here. The acceleration at the top of the CRDM housing is reduced from the fixed-base condition by a factor of 10 (7.70 g to 0.78 g) if the equipment is isolated using system 4 and by a factor of 4 (7.70 g to 1.84 g) if system 1 is implemented.

Table 1 – 80th percentile horizontal accelerations and displacements

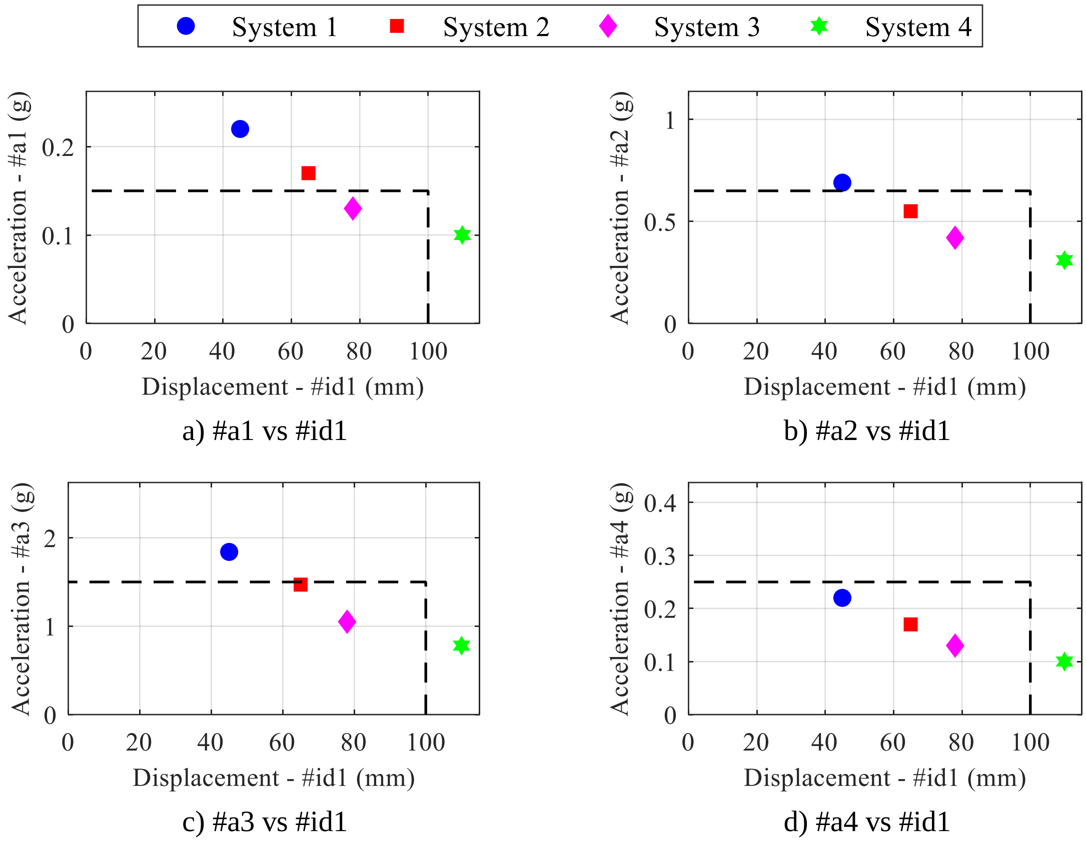
Parameter		**Fixed-base**	**Isolation systems**			
			1	**2**	**3**	**4**
Geomean horizontal accelerations (g)	#a1	0.67	0.22	0.17	0.13	0.10
	#a2	3.20	0.69	0.55	0.42	0.31
	#a3	7.70	1.84	1.47	1.05	0.78
	#a4	1.21	0.37	0.28	0.21	0.15
	#a5	1.80	0.47	0.36	0.27	0.19
Horizontal displacements (mm)	#d1	23	6	5	4	3
	#d2	26	6	5	4	3
	#d3	1	1	1	1	1
	#d4	4	2	2	2	2
	#id1	-	45	65	78	110

The relative displacements in the EI building are much smaller than those in the fixed-base building. Displacement #d1, at the top of the reactor vessel relative to its point of attachment is 23 mm in the fixed-base building but 6 mm (3 mm) in EI building with system 1 (system 4). As the isolation system is changed from 1 to 4, the accelerations (#a1 through #a5) and displacements (#d1 through #d4) are reduced, but displacement across the isolation interface (#id1) is increased from 45 mm to 110 mm. A process for selecting an optimal isolation system among the four considered, based on the design spaces for these pieces of equipment, is illustrated next.

5.2. Selecting an optimal isolation system based on hypothetical design spaces

Seismic, mechanical and system analysis will be needed to generate equipment-specific design spaces. Herein, hypothetical design spaces, using accelerations (#a1 through #a4) and displacement (#id1) only, are proposed to illustrate the process by which acceptable seismic isolation systems could be selected. Arbitrary limiting values were assigned to the accelerations: #a1 (0.15 g), #a2 (0.65 g), #a3 (1.5 g), and #a4 (0.25 g). (These accelerations correspond approximately to expected responses for an input peak ground acceleration of 0.06 g at the base of the building at the INL site.) The limiting displacement across the isolation interface was set at 100 mm in all cases. (This displacement could represent the deformation capacity of umbilical lines crossing the isolation interface at the levels of the floor slab, reactor head, top of CRDMs, and head and bottom of the SG.)

The four design spaces (dashed black lines) are presented in Fig. 7, together with the results of the non-linear dynamic analysis for the four isolation systems. Fig. 7a and 7b are design spaces for the RV. Fig. 7c and 7d are the design spaces for the CRDM housing and the SG, respectively.



a) #a1 vs #id1

b) #a2 vs #id1

c) #a3 vs #id1

d) #a4 vs #id1

Fig. 7 Selecting an optimal equipment-level isolation system using hypothetical design spaces

Data points within the design space are acceptable. Data points outside the design space are unacceptable, and would require redesign of the equipment for a greater seismic capacity, resulting in an increase in fabrication cost. For the RV alone, only isolation system 3 provides solutions within the design spaces of Fig. 7a and 7b. Isolation systems 2 and 3 would be acceptable for the CRDM housing alone. Isolation systems 1, 2 and 3 would be acceptable for the SG alone. Given that the three pieces of equipment share a common isolation system, only the use of isolation system 3 would avoid the need to redesign and qualify the equipment and its connections.

5.3. Pathway to NoaK safety-class equipment

Equipment-based seismic isolation systems provide two important benefits to advanced reactors: 1) equipment designed for operational efficiency, and 2) a technical pathway to NoaK equipment, such as the integrated RV and SG of Fig. 1. By eliminating the impact of the seismic load case, equipment weight, complexity, and cost will be reduced. By making possible order books for N pieces of identical equipment, investments will be spurred in design optimization, advanced manufacturing, and supply chains, driving down OCC. The standardization made possible by equipment-based isolation will drive down engineering costs (i.e., analysis, design, regulatory review, seismic qualification), which are likely of the same order as the FoaK fabrication cost for much of the safety-class equipment in an advanced reactor [8]. The required engineering for a NoaK equipment installation would be limited to the analysis, design, testing and regulatory review of the isolation system, and testing of the isolators.

For the example considered here, and the design spaces of Fig. 7, there is margin with isolation system 3, namely, the DBE shaking could be increased with no need to re-engineer or modify the RV or SG. A different spectral shape for design, which would likely accompany a change in site, could be accommodated by identical equipment supported by a FP isolation system with a different sliding radius (period) and coefficient of sliding friction or a lead-rubber bearing isolation system.

6. Closing remarks

The goal of the ARPA-E MEITNER project described in this paper is reducing the OCC per MWE and LCOE for advanced reactors. The seismic load case is an important contributor to both OCC and LCOE because earthquake shaking renders each NPP design to be bespoke, namely, each NPP is essentially a FoaK. Seismic isolation offers a clear pathway to drastic reductions in both OCC and LCOE regardless of whether the building or internal equipment is isolated.

This paper presents a pathway to NoaK equipment using equipment-level seismic protective systems. A paradigm shift in nuclear design practice is proposed, wherein safety-class equipment is designed for operational loadings only, its resultant seismic capacity is established and described in terms of a design space, and that capacity is used to drive the choice of a seismic protective (isolation) system. Such a process focuses on reducing or eliminating the impact of the seismic load case on the functionality and cost of safety-class equipment, with the objectives being to standardize equipment designs, eliminate engineering costs, and build order books for N pieces of identical equipment. Reducing or eliminating the impact of the seismic load case on equipment design and fabrication could shrink the size of equipment, permit design for operational efficiencies and maximize power output, and significantly reduce FoaK (and NoaK) equipment cost. Eliminating engineering costs will substantially reduce, perhaps by a factor of 2, the total capital cost of equipment. Order books for N pieces of identical equipment will spur innovation and encourage investment in the nuclear supply chain.

The paradigm shift is demonstrated using a generic HTGR building equipped with three pieces of safety-class equipment: RV, SG, and CRDM housing. Designs for the reactor building and the equipment were developed per ASCE/SEI Standards 4 and 43, ACI 349, and the ASME Boiler and Pressure Vessel code. Numerical models of the reactor building and the safety-class equipment were developed and analyzed for ground motions consistent with DBE shaking at the INL site.

Hypothetical design spaces were proposed for the equipment in the HTGR. Four seismic protective systems, specific to the building and the INL site, were investigated to identify solutions that fall within the design spaces. One of the four isolation systems was optimal for the chosen building, site, and equipment, and eliminated the impact of the seismic load case on the design of the equipment. An identical (NoaK) equipment could be used in the same building, at a different site, with the only possible change being an alternate isolation system.

7. Acknowledgements

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