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COST BASIS FOR UTILIZING SEISMIC ISOLATION IN NUCLEAR POWER PLANTS

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ABSTRACT

The benefits of seismically isolating nuclear power plant buildings, in terms of reducing seismic risk, are well established but the possible impacts on overnight capital cost are unknown. Projects funded by EPRI and ARPA-E are now underway to characterize possible reductions in overnight capital cost of new build plants, with a focus on the financial impact of the seismic load case. The EPRI-funded study is addressing the base isolation of reactor buildings and the ARPA-E MEITNER project is assessing the use of equipment-based seismic protective systems in advanced reactors.

Two *generic* reactor buildings were designed to provide data on equipment weights and lateral accelerations as a function of incremented levels of earthquake shaking. One building houses a molten chloride fast reactor and the other a high-temperature gas reactor. Each building was populated with three pieces of equipment: a reactor vessel, a steam generator and a housing for a control rod drive mechanism. Response-history analysis was performed using earthquake ground motions consistent with the seismic hazard at the Idaho National Laboratory site, in Idaho Falls, ID. The minimum required wall thicknesses for the reactor vessels and steam generators in these buildings, for operational and incremented earthquake loads, are reported. Lateral accelerations, which are used for the seismic design of the internals in these vessels and for the control rod drive mechanisms, are presented for incremented peak ground shaking of the buildings. The benefits of base isolating the two buildings, in terms of reduced thickness of vessel walls and horizontal accelerations of vessel internals and control rod drive mechanisms are identified. A questionnaire, which seeks to characterize the increase in total cost (i.e., analysis, design, qualification, and fabrication) of equipment for incremented levels of earthquake shaking, is summarized. The questionnaire will be transmitted to consultants, equipment fabricators and suppliers, nuclear steam system suppliers, and operators of commercial nuclear reactors. The responses to the questionnaire and follow-on studies will be presented at SMiRT26.

INTRODUCTION

The recently published report *Future of Nuclear Energy in a Carbon-Constrained World* (Buongiorno *et al.*, 2018) identifies the important role that could (should) be played by nuclear energy in decarbonization of global electricity production. New nuclear power plants will need to be constructed to achieve the goal of decarbonization, and to replace aging plants that are currently planned for retirement: 12 in the United States in the next 7 years.

The major impediment to the deployment of new large light water, small modular, and advanced nuclear reactors is the high projected overnight capital cost (OCC) per MWe, and the time required to design, review, and construct plants, which to date in the United States have always been First-of-a-Kind. Unlike other industries, including oil, gas and petrochemical, there are no modern, non-proprietary cost data available to engineers to aid decision making at the scheme design phase for a nuclear power plant.

The seismic load case is a key contributor to the OCC of a new nuclear power plant, with recent anecdotal evidence indicating that the *seismic penalty* may now be greater than 30% in some cases. The last cost-oriented dataset that addressed the impact of the seismic load case was assembled by Stevenson (1981, 2003), who estimated the incremented cost of a conventional (Generation II) 1100 to 1300 MWe large light water reactor as a function of increasing earthquake shaking. Stevenson, using data from the 1970s, concluded that the cost of increasing the seismic capacity of a plant from a peak ground acceleration of 0.2 g to 0.6 g was approximately 10% of the total plant cost: substantially less than more recent estimates.

To help characterize possible reductions in overnight capital cost of new build plants, the Electric Power Research Institute (EPRI) funded a project with the goal of developing a modern dataset on earthquake-related contributors to the overnight capital cost of new build nuclear reactors: a first-of-a-kind study since the 1980s. The project aims to answer six specific questions, namely, (1) Is there a financial argument to be made for seismic isolation of nuclear power plants?, (2) What are the cost savings for nuclear power plant owners if seismic isolation is deployed?, (3) Can the cost-benefit of seismic isolation systems be parameterized according to specific structural geometries and designs?, (4) Can seismic isolation systems be applied to deeply embedded reactor buildings?, (5) Can equipment qualification be reduced, simplified, or avoided in new build plants if seismic isolation is deployed, and (6) What additional research is needed to implement the use of seismic isolation if it is found to be viable and cost effective for new build plants? A focus of the EPRI-funded study is seismic isolation of reactor buildings and associated costs and benefits. In parallel, ARPA-E is funding a MEITNER project that aims to reduce the overnight capital cost of advanced reactors using equipment-based seismic protective systems. One of the tasks in the ARPA-E project is to establish possible reductions in the total cost of safety-class equipment to be installed in advanced reactors, as enabled by the use of equipment-based seismic protective systems.

The recent publication of three NUREG/CRs (Kammerer *et al.*, 2019; Kumar *et al.*, 2019a; Kumar *et al.*, 2019b) provides the technical basis for the implementation of seismic (base) isolation in new build nuclear power plants of any class, including those identified above and micro-reactors. Those developments are not discussed here. Rather, this paper addresses the equally important subject of overnight capital cost of conventional and isolated new build plants.

Two reactor buildings were designed by the authors, one for a molten chloride fast reactor (MCFR) and the other for a high-temperature gas reactor (HTGR), to build a dataset that would enable industry experts to identify the cost impacts of the seismic load case, and by extension the commercial viability of seismic isolation. The authors worked with experts at TerraPower (MCFR) and X-energy (HTGR) to develop *generic* designs for equipment in these reactor buildings. The two buildings were each populated with three pieces of safety-class equipment: a reactor vessel, a steam generator and a control rod drive mechanism (CRDM) housing. Sample designs were developed for these pieces of equipment for a) operational loadings and b) loadings associated with incremented earthquake shaking. To calculate stresses in vessel walls and lateral accelerations due to earthquake loading, the vessels (shell elements) and CRDM housings (beam elements) were included in the numerical model for dynamic analysis. Ground shaking effects were characterized by geomean horizontal peak ground acceleration, with amplitudes of 0.1 g, 0.2 g, 0.3 g, and 0.5 g.

REACTOR BUILDING SITE

The two reactor buildings were sited within the boundaries of the Idaho National Laboratory (INL) in the northwest United States. The characterization of the seismic hazard at INL for a return period of 10,000 years, and the assumed starting point for calculating design-basis earthquake (DBE) shaking at sites of nuclear power plants, is presented in Yu *et al.* (2018) and not repeated here. Earthquake ground motions consistent with the DBE shaking at the INL site were generated by Yu *et al.* (2018), and those were utilized here for response-history analysis of the reactor buildings. To establish the impact of the seismic load case on weights of and accelerations in equipment, ground shaking effects were characterized by a) the shape of the INL spectrum of Figure 1, and b) geomean horizontal peak ground acceleration, with incremented amplitudes of 0.1 g, 0.2 g, 0.3 g, and 0.5 g.

Figure 1 presents the geometric mean, DBE horizontal shaking spectrum for the INL site for a return period of 10,000 years. A linearized Regulatory Guide (RG) 1.60 spectrum (USNRC, 2014), anchored to a peak ground acceleration of 0.3 g, is also plotted in the figure. The ordinates of the INL spectrum exceed those of the RG spectrum at frequencies greater than 20 Hz. At lower frequencies, and of importance to the two buildings considered here, the ordinates of the INL spectrum are less than those of the RG spectrum.

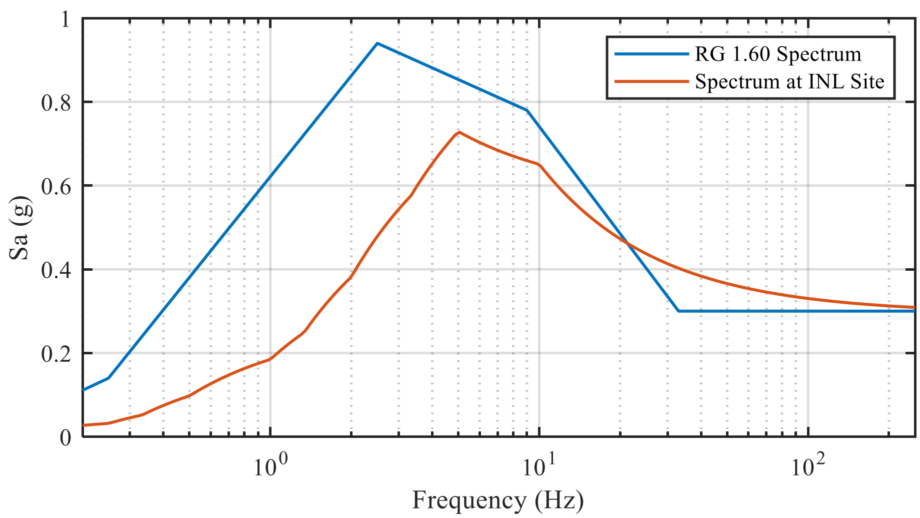


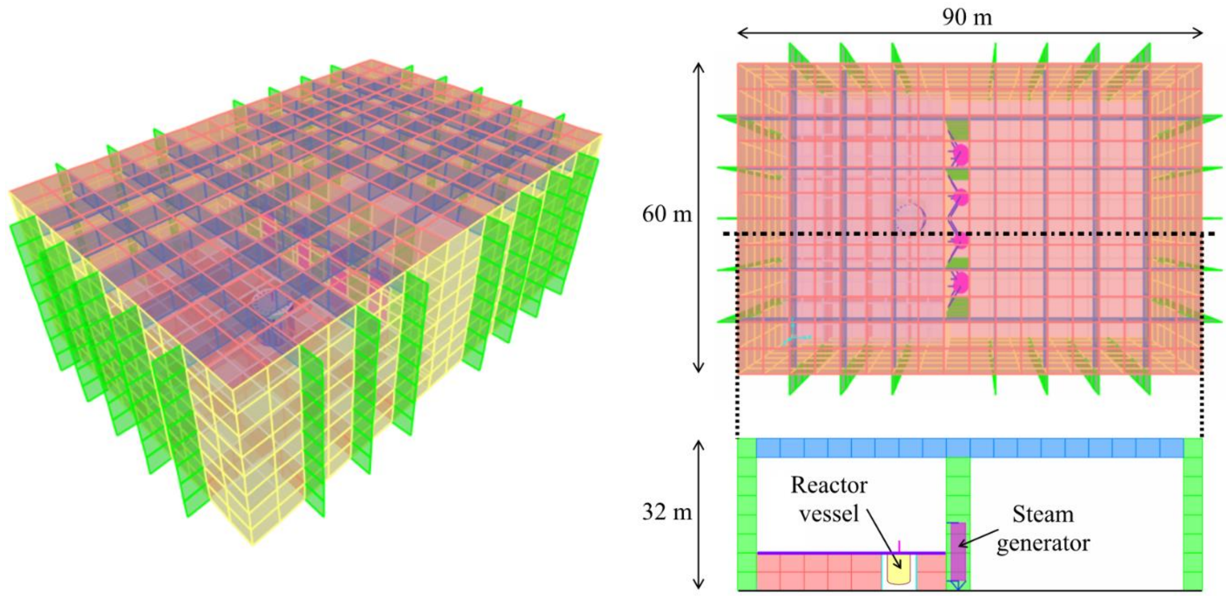
Figure 1. INL and RG 1.60 spectra for horizontal shaking at the ground surface

REACTOR BUILDINGS, EQUIPMENT, AND ISOLATION SYSTEM

Molten Chloride Fast Reactor

The generic molten chloride fast reactor is housed in a reinforced concrete building (building #1) with two compartments, the first housing the reactor vessel, and the second the steam generators. The overall building dimensions are 90 m by 60 m, and the height from the basemat to the top of the roof is 32 m. The first compartment has two stories whereas the second is one story. The building frame includes perimeter walls and a center wall that separates the two compartments. Buttresses provide lateral stiffness to the walls. The building framing was sized by response-spectrum analysis to resist design-basis shaking consistent with the RG 1.60 spectrum of Figure 1, anchored to a peak ground acceleration of 0.3 g. Figure 2 shows the isometric view of the building model in SAP2000 (CSI, 2019) and plan and sectional views of the building.

The walls and slabs were modeled using shells of an appropriate thickness and elastic modulus. A damping ratio of 4% was assigned to the reinforced concrete and the safety-class equipment. The dominant translational frequencies of the building are in the range of 5 to 7 Hz: near the peak of the INL spectrum in Figure 1. The translational frequency of the suspended floor that supports the reactor vessel (see the solid purple line in the cross section of Figure 2b) is 25 Hz. (Accordingly, amplification of ground motion from the basemat to the suspended floor is small, and less than 1.3).



a. Isometric view b. Plan view and cross section

Figure 2. Reactor building #1

Generic information on construction of the reactor vessel, steam generators (including the pressures inside the reactor vessel and steam generators), and the CRDM housing were extracted from the literature and confirmed as reasonable by TerraPower. The reactor vessel is supported at its head, at the level of the suspended floor in the two-story compartment. The vessel is surrounded by a cylindrical reinforced concrete wall, supported on the basemat. The vessel is 5 m in diameter and 6 m in height, including a domed base. The operating gas pressure inside the vessel was assumed to be 0.5 MPa (approximately 5 bars). The CRDM housing is attached to the reactor head, and was assumed to be composed of 2.5 m long, 250 mm diameter tubes. The reactor vessel and its CRDM housing were assumed to be constructed from 316 stainless steel

Four steam generators are located in the one-story compartment, as shown in Figure 2b. Each steam generator is 3 m in diameter and 14 m tall and assumed to be constructed from 316 stainless steel. Each steam generator was assumed to be supported horizontally and vertically at its base and laterally braced at its top by the wall that separates the two compartments. The assumed internal operating pressure was 1 MPa (approximately 10 bars).

High Temperature Gas Reactor

The generic high temperature gas reactor (HTGR) is housed in a multi-story, reinforced concrete structure (building #2) with two major compartments, one housing the reactor vessel, and the other a steam generator.

The building dimensions are 23 m by 20 m in plan, and the height from the basemat to the top of the roof is 42 m. The building framing was sized by response-spectrum analysis to resist design-basis shaking consistent with the RG 1.60 spectrum of Figure 1, anchored to a peak ground acceleration of 0.3 g. Figure 3 presents an isometric view of the building model in SAP2000.

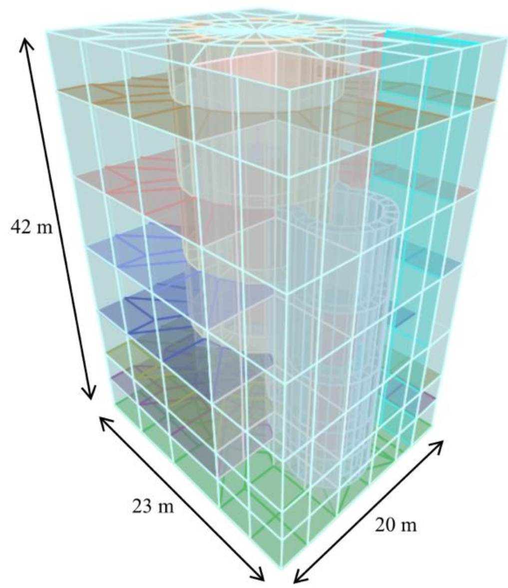


Figure 3. Reactor building #2

The walls and slabs were modeled using shells of an appropriate thickness and modulus. A damping ratio of 4% was assigned to the reinforced concrete and the safety-class equipment, per the seismic analysis of building #1. The dominant translational frequencies of the building are in the range of 5 to 6 Hz: near the peak of the INL spectrum of Figure 1.

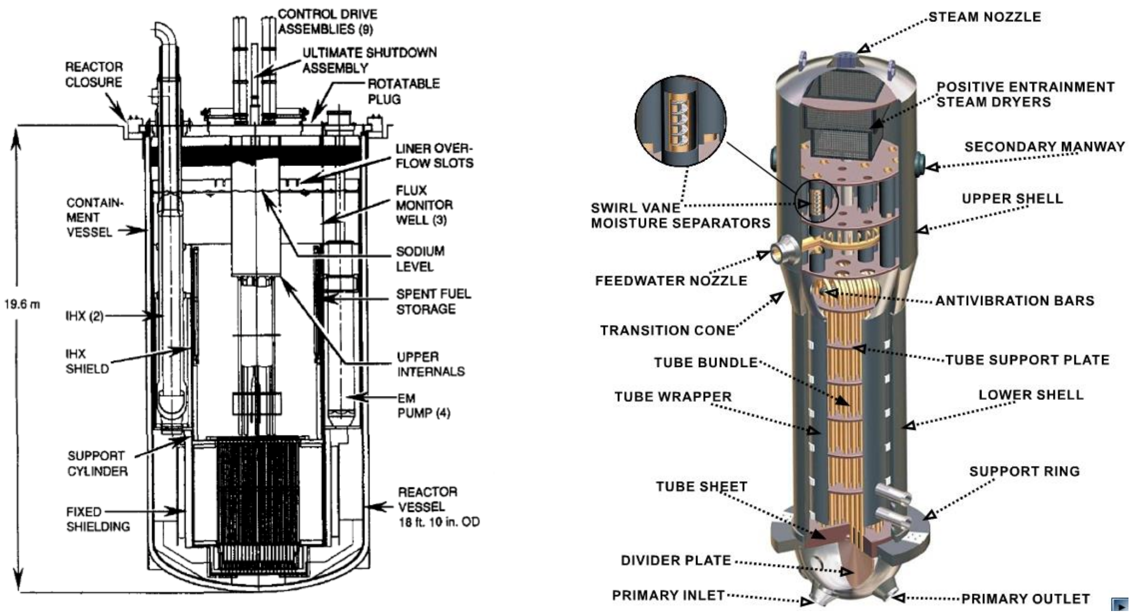
Generic information on construction of the reactor vessel, steam generator (including the gas pressures inside the reactor vessel and steam generator), and the CRDM housing were extracted from the literature and confirmed as reasonable by X-energy. The reactor vessel is supported at its base in the first compartment, approximately 13 m above the basemat. The reactor vessel is 4.5 m in diameter and 14 m in height. The operating gas pressure in the reactor vessel was assumed to be 7 MPa (approximately 70 bars). The CRDM housing is attached to the reactor head and assumed to be composed of 2.5 m long, 250 mm diameter tubes: identical to those in the molten chloride fast reactor building. The reactor vessel and its CRDM housing were assumed to be constructed from SA 508 low alloy steel.

The steam generator is 3.5 m in diameter and 15.5 m tall, including a domed base. It is installed in the second compartment and assumed to be supported approximately 5 m below its head by trunnion mounts, at the same level as the base of the reactor vessel. The internal operating pressure was assumed to be 7 MPa. The steam generator was assumed to be constructed from SA 516 low alloy steel.

Equipment

Six *generic* pieces of equipment are considered here, 2 reactor vessels, 2 CRDM housings, and 2 steam generators. The pieces of equipment are: #1, reactor vessel in building #1; #2, CRDM housing, attached to the top of the reactor vessel in building #1; #3, steam generator in building #1; #4, reactor vessel in building #2; #5, CRDM housing, attached to the top of the reactor vessel in building #2; and #6, steam generator in building #2.

Figure 4 shows cut-away views of an advanced reactor vessel (circa 1997) and a steam generator (for a pressurized water reactor). These views are provided here to illustrate key components of each of these pieces of equipment: 1) a reactor, which is composed of a vessel, a head, and internal equipment, and 2) a steam generator, which is composed of a vessel and internal equipment. The cost of the vessels and their internals are a function of material weight (quantified for the vessels) and the horizontal acceleration of the vessel (quantified for the internals and the CRDM housing).



a. Reactor (Gluekler, 1997) b. Steam generator (www.thermopedia.com)

Figure 4. Internal construction of the reactor and steam generator

Isolation System

One isolation system was developed for each building and neither was optimized. Single concave Friction Pendulum bearings were used for the isolation system. The isolators were modeled in SAP2000 using the friction isolator link element. The sliding period of the isolators was equal to 3 seconds and the coefficient of sliding friction was assumed equal to 0.06. Building #1 incorporated 70 isolators. Building #2 incorporated 20 isolators.

RESPONSE-HISTORY ANALYSIS

Response-history analysis was performed for the fixed-based and isolated reactor buildings. The ground motions in Yu *et al.* (2018), which are consistent with the shape of the INL spectrum of Figure 1, were amplitude scaled to geomean peak horizontal ground accelerations of 0.1 g, 0.2 g, 0.3 g, and 0.5g. Thirty sets of ground motions were developed for each intensity of earthquake shaking. The ground motions were input at the base of the model and soil-structure-interaction was ignored. The products of the response-history analyses, for incremented intensities of earthquake shaking, were 1) equipment weight normalized by the benchmark value for operational loadings, 2) horizontal acceleration of the vessel internals at a representative location, and 3) peak horizontal acceleration at the upper end of the CRDM housing.

To calculate vessel weight, the minimum thickness of its wall was calculated using Section III, Division 5 of the 2017 ASME Boiler and Pressure Vessel code (ASME, 2017). The minimum thickness was calculated using the ASME allowable design stress intensity for demands associated with hoop and axial stresses in the vessel wall. The allowable stress intensities were calculated for the materials assumed for the vessels at appropriate operating temperatures.

Earthquake-induced shear stresses were determined from the response-history analysis. Stresses at the points of attachment, which are influenced by load and stiffness discontinuities, were not used for calculations of required wall thickness. Rather, shear stresses in the immediate vicinity of supports and elsewhere in the vessel were monitored and then used for code-based calculations. The earthquake-induced shear stresses were calculated at the 80^{th} percentile per ASCE/SEI Standard 4-16 (ASCE, 2017), and then increased by 25% because the assumption of 4% modal damping is too high for the safety-class equipment, for which 2% (or less) would be appropriate. (The modes involving significant response of the equipment are coupled with building response and it was not possible to separately assign damping to the reinforced concrete and the equipment.) The shear stresses from the operational loadings and the earthquake loading (as adjusted above) were combined per the ASME code, and compared with the allowable stress intensity. The wall thickness was increased in increments of 1 mm when input ground shaking produced combined stresses in excess of the limiting value.

The horizontal accelerations at the point of attachment of the equipment, at a representative location for the vessel internals (see Figure 4), and at the upper end of the CRDM housing were also determined from the response-history analysis. The accelerations were calculated at the 80^{th} percentile. The accelerations of the internals and at the upper end of the CRDM housings were increased by 25% to account for their 2% (or less) damping.

Results and Discussion

Earthquake shaking will affect the design, detailing and fabrication of equipment. For the reactor vessels (e.g., pieces #1 and #4) and the steam generators (e.g., pieces #3 and #6), increased shaking intensity will require a) an increase in the thickness of the wall of the vessel beyond a threshold intensity of shaking and b) lateral bracing and strengthening of the internal equipment, and likely adjustments to the internal dimensions of the vessel. Table 1 characterizes the effect of increasing earthquake shaking on the weight of the reactor vessels and steam generators. The weight of the fabricated component, designed for operational loadings only (i.e., no seismic load) is set equal to 100 to normalize the results, and increased in units of 10. The lateral acceleration, in g, of the internals designed for operational loadings only, is 0. Table 2 characterizes the peak horizontal accelerations at the points of attachment of equipment. The representative horizontal accelerations of the internals in the reactor vessels and steam generators, and at the top of the CRDM housings are presented in Table 3. Two sets of data are provided in each table: fixed-base (i.e., conventional construction) and base isolated.

For the fixed-base buildings, the *seismic penalty*, in terms of increased vessel weight, is greatest for the steam generator in building #1 (100 units to 390 units, for PGA = 0.0 to PGA = 0.5g, respectively) and least for the steam generator in building #2 (100 units to 130 units, for PGA = 0.0 to PGA = 0.5g, respectively). If increase in normalized weight is considered a reasonable marker for increases in fabrication cost, and if fabrication cost increases linearly or quadratically with vessel weight, an estimate can be made of the seismic penalty for fabricated equipment. Given that the cost of each of these pieces of equipment will be tens of millions of USD, and perhaps 100s of millions of USD for a reactor vessel with a high-power output, minimizing the effects of the seismic load case should be a goal of design.

The *seismic penalty* for equipment in the isolated buildings is significantly smaller than in the fixed-base structures. For the reactor vessels in the isolated buildings of Table 1, a 20% (building #1) and 10% (building #2) increase in vessel weight over that required for operational loadings would provide sufficient capacity to resist earthquake shaking with a peak ground acceleration of 0.50 g. If the *seismic penalty* is

Table 1: Normalized weight of reactor vessels and steam generators in buildings #1 and #2

PGA (g)	Building #1				Building #2			
	Reactor vessel		Steam generator		Reactor vessel		Steam generator	
	Fixed-base	Isolated	Fixed-base	Isolated	Fixed-base	Isolated	Fixed-base	Isolated
0.00	100	100	100	100	100	100	100	100
0.10	120	120	140	140	110	110	110	110
0.20	140	120	210	140	130	110	110	110
0.30	170	120	270	140	160	110	110	110
0.50	230	120	390	140	210	110	130	110

Table 2: Peak horizontal acceleration at points of attachment of equipment in buildings #1 and #2

Piece #	Peak horizontal ground acceleration							
	0.1 g		0.2 g		0.3 g		0.5 g	
	Fixed-base	Isolated	Fixed-base	Isolated	Fixed-base	Isolated	Fixed-base	Isolated
1	0.16	0.10	0.32	0.12	0.48	0.15	0.80	0.18
2	0.16	0.10	0.32	0.12	0.48	0.15	0.80	0.18
3	0.16	0.10	0.32	0.12	0.48	0.15	0.80	0.18
4	0.23	0.09	0.47	0.11	0.67	0.13	1.17	0.15
5	3.19	0.33	6.38	0.44	9.43	0.51	16.0	0.59
6	0.23	0.09	0.47	0.11	0.67	0.13	1.17	0.15

Table 3: Horizontal acceleration of internals in reactor vessels and steam generators and at the top of the CRDM housings in buildings #1 and #2

Piece #	Peak horizontal ground acceleration							
	0.1 g		0.2 g		0.3 g		0.5 g	
	Fixed-base	Isolated	Fixed-base	Isolated	Fixed-base	Isolated	Fixed-base	Isolated
1	0.54	0.20	1.08	0.27	1.62	0.30	2.70	0.37
2	0.69	0.18	1.39	0.22	2.08	0.24	3.47	0.27
3	0.53	0.18	1.05	0.23	1.58	0.26	2.63	0.30
4	3.19	0.33	6.38	0.44	9.43	0.51	16.0	0.59
5	5.82	0.59	11.6	0.85	16.8	0.97	29.1	1.13
6	1.33	0.22	2.67	0.29	3.44	0.35	6.67	0.36

small, as enabled for the equipment in these two buildings by base isolation, the goal of using Nth-of-a-Kind equipment, optimized for operational loadings but possessing sufficient seismic capacity, across all sites in the United States becomes achievable.

Of importance to the design of internals in the vessels and the CRDM housings, are the horizontal accelerations that result from earthquake shaking. Tables 2 and 3 present information at the points of attachment of equipment and at representative locations on the equipment, respectively. It is evident from the accelerations reported in these tables, and in particular in Table 3, that earthquake shaking will pose unique challenges to the design and fabrication of vessel internals and control rod drive mechanisms, and add substantially to their cost. In contrast, the corresponding accelerations in the isolated buildings are considerably smaller, with reductions by a factor of between 6 and 18 possible for a PGA of 0.3 g.

QUESTIONNAIRE

The data of Tables 1, 2 and 3, will be transmitted to consultants, equipment fabricators and suppliers, nuclear steam system suppliers, and operators of commercial nuclear reactors, together with the 13 questions below, which if answered will provide important insight into the increase in overnight capital cost of new build reactors due to the seismic load case. Such insight may enable improved decision-making regarding equipment design and deployment, and demonstrate the cost impact of seismically isolating either reactor buildings or individual pieces of equipment. All costs will be normalized by cost question #4 (=100).

1. Cost to analyze/design (i.e., engineering) for operational loadings (horizontal peak ground acceleration = 0.0 g) and calculate its seismic capacity. The costs associated with conceptual design and nuclear physics should not be included.
2. Cost to seismically qualify the first unit: by analysis for pieces #1, #3, #4 and #6, and by testing for pieces #2 and #5.
3. Cost to prepare for, and of regulatory review
4. Cost to fabricate the first unit, including materials, tooling, etc.
5. Cost to fabricate the tenth unit identical to the first unit
6. Cost to increase seismic capacity of the first unit for PGA = 0.1 g. Include the costs of new analysis, design, seismic qualification, and regulatory review
7. Cost to fabricate the first unit with seismic capacity associated with PGA = 0.1 g. Use the weights (or accelerations for CRDM housings) in the tables above to estimate the increased fabrication cost
8. Cost to increase seismic capacity of the first unit for PGA = 0.2 g. Include the costs of new analysis, design, seismic qualification, and regulatory review
9. Cost to fabricate the first unit with seismic capacity associated with PGA = 0.2 g. Use the weights (or accelerations for CRDM housings) in the tables above to estimate the increased fabrication cost
10. Cost to increase seismic capacity of the first unit for PGA = 0.3 g. Include the costs of new analysis, design, seismic qualification, and regulatory review
11. Cost to fabricate the first unit with seismic capacity associated with PGA = 0.3 g. Use the weights (or accelerations for CRDM housings) in the tables above to estimate the increased fabrication cost
12. Cost to increase seismic capacity of the first unit for PGA = 0.5 g. Include the costs of new analysis, design, seismic qualification, and regulatory review
13. Cost to fabricate the first unit with seismic capacity associated with PGA = 0.5 g. Use the weights (or accelerations for CRDM housings) in the tables above to estimate the increased fabrication cost

CLOSING REMARKS

The major impediment to the deployment of new large light water, small modular, and advanced nuclear reactors is the high projected overnight capital cost (OCC) per MWh and the required time for design, review, and construction. Unlike other industries, , there are no modern, non-proprietary cost data available to engineers to aid important decision making at the outset of a project to design a new plant. A plan is proposed to gather such data, developed around the design of two fundamentally different reactor buildings and reactor types. Safety-critical equipment was selected and designed for each building following the provisions of the ASME Boiler and Pressure Vessel code. The seismic penalty, in terms of increased equipment weight and lateral acceleration, was established for incremented levels of earthquake shaking, assuming both buildings are sited inside the perimeter of the Idaho National Laboratory. Neither the buildings nor the equipment is specific to a design now underway and the data provided in the paper can be considered *generic*. A questionnaire has been prepared to elicit information on the impact of the seismic load case and it will be distributed to consultants, equipment fabricators and suppliers, nuclear steam system suppliers, and operators of fleets of commercial nuclear reactors. Results of the questionnaire will be presented at SMiRT26.

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