Towards standardized advanced nuclear reactors: seismic isolation and the impact of the earthquake load case

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Abstract

Advanced nuclear reactors have a key role to play in global decarbonization. Impediments to the widespread deployment of advanced reactors is their projected high overnight capital cost (OCC) and levelized cost of energy, and time required to analyze, design, license, construct, and commission. The earthquake load case is one of the key cost drivers for a new build nuclear plant, because near-surface soils and seismic hazard are different at each site, requiring site-specific analysis, design, engineering, qualification, licensing, and regulatory review, essentially making every design First-of-a-Kind (FoaK). To enable deployment at the scale needed for deep decarbonization, the cost and time impact of the seismic load case must be significantly reduced or eliminated, and plants must be standardized. Seismic base isolation has been proven to considerably reduce the earthquake response of structures and equipment but has yet to be applied to a nuclear power plant in the United States, in part because the financial impacts, positive or negative, are not known. Because no modern, non-proprietary data exist to characterize the influence of the seismic load case on OCC, it is impossible to confidently quantify the financial benefits of seismic isolation.

To assemble modern cost data on the influence of the seismic load case, scheme designs of two fundamentally different advanced reactor buildings were developed. Both buildings were equipped with three bespoke pieces of safety-class equipment and analyzed for incremented levels of earthquake shaking to quantify the seismic penalty on equipment, in terms of vessel weights and horizontal accelerations. Using analysis results, a questionnaire was developed and transmitted to domain experts to collect cost data on engineering and fabrication costs for these unique pieces of safety-class equipment. Synthesis of the cost data showed that the seismic load case significantly affects the capital cost (sum of engineering and fabrication cost) of safety-class equipment, with engineering costs being comparable to fabrication costs. Standardization of safety-class equipment is made possible by seismic isolation, that is, equipment designed for minimal seismic robustness can resist earthquake shaking at a site of much higher seismic hazard. The predicted average reduction in capital cost enabled by seismic isolation is a factor of two for FoaK equipment and a factor of five for standardized equipment.

1. Introduction

Nuclear power has a significant role to play in decarbonizing the global economy, mitigating climate change, and meeting future demands for energy (Buongiorno *et al.*, 2018; ETI, 2020; IAEA, 2020a; IAEA, 2020b; IEA, 2019; Ingersoll and Gogan, 2020; Partanen *et al.*, 2019). At the time of this writing, nuclear power contributes about one quarter of global low carbon electricity (EMBER, 2021). The major impediments to the widespread deployment of new nuclear power plants (i.e., large light water, small modular, and advanced reactors) is the projected high overnight capital cost (OCC) and levelized cost of energy (LCOE), and the time required to site, design, review, license, construct, and commission them.

Figure 1 presents the total capital cost (in 2017 USD) of recently completed and ongoing nuclear projects in eight countries. The plants in the United States and western Europe, enclosed by the red dashed rectangle, are all First-of-a-Kind (FoaK) projects, being built after decades of construction inactivity, requiring substantial capacity building in supply chains and labor forces. In clear contrast, the majority of the plants constructed elsewhere have benefited from continuous build (and improvement) programs, delivering units at much lower cost and on schedule. New build reactors must be delivered for between \$2,500 and \$3,000/kWe to be cost-competitive with gas-fired plants: a five-fold reduction from the current cost of the Plant Vogtle expansion in the United States of approximately \$13,000/kWe, assuming 2.1 GWe at a cost of \$27B per Table 1.1 of Georgia Power (2020). Note that in the multiunit data points on the right side of the bar chart, the costs of the initial units are the top end of the bars and the last units are the bottom, so they not only represent a range, but a progression from higher cost to lower cost.

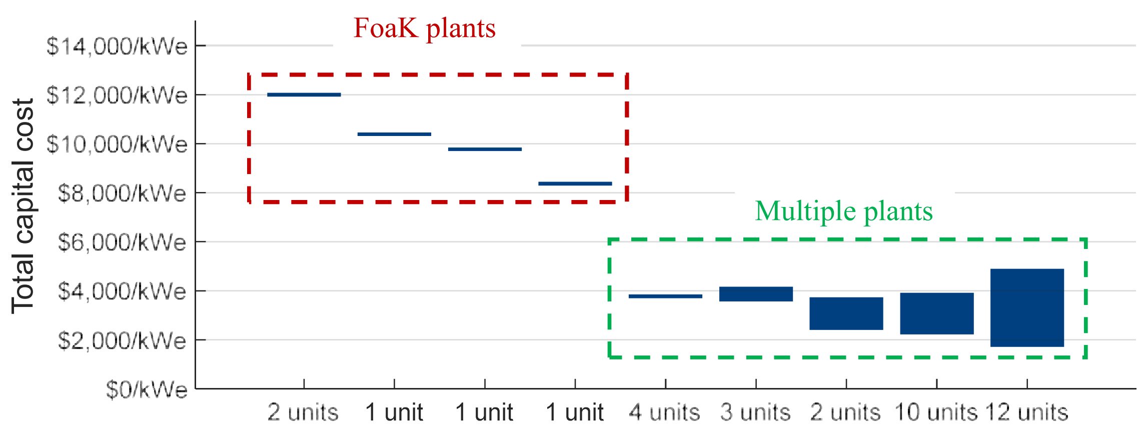


Figure 1. Total capital cost of recently completed and ongoing nuclear projects (adapted from ETI (2020))

Figure 2 deconstructs the capital cost of nuclear projects in the United States, Western Europe, and elsewhere in the world. Evidence suggests that aside from the higher direct costs of materials, equipment, and labor in the United States and Western Europe, the long build times of FoaK projects lead to substantially greater time-based indirect costs (e.g., engineering, supervision, project management, rental site infrastructure), greater interest payments, and higher interest rates due to project risk (ETI, 2020). In addition, FoaK builds using incomplete construction documentation at project start has led to significant delays, further adding to project cost (EPRI, 2019).

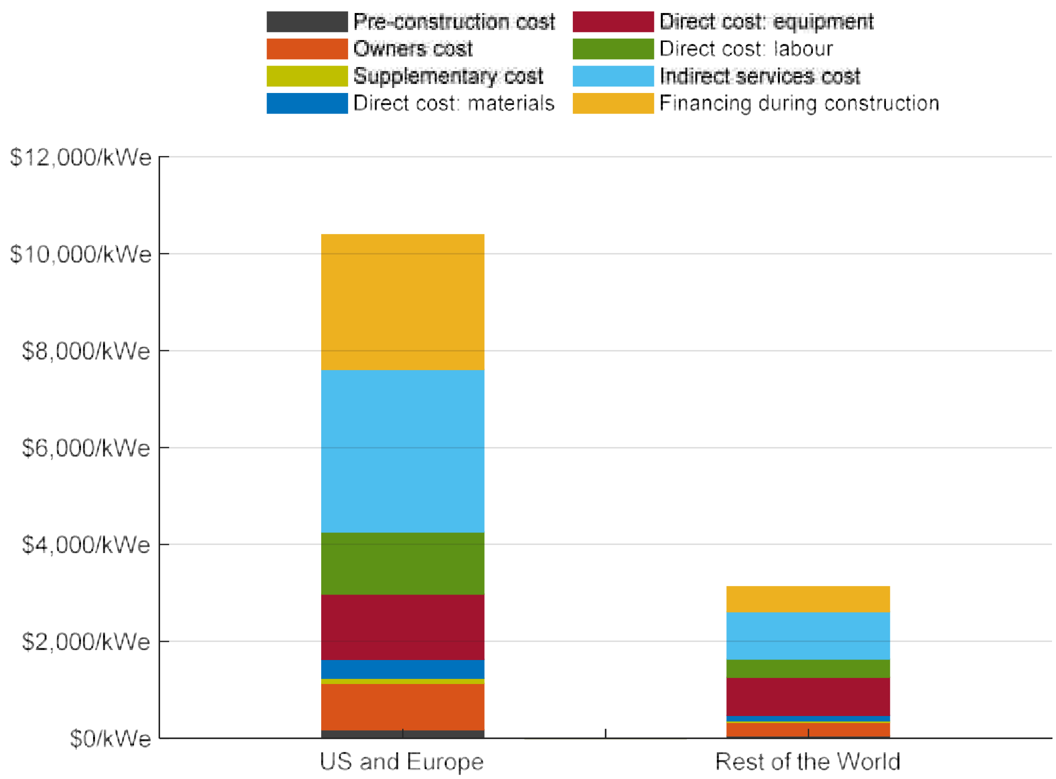


Figure 2. Capital cost breakdown (adopted from ETI (2020))

To make meaningful contributions towards deep decarbonization, advanced nuclear reactors must be cost competitive with both renewables (e.g., wind and solar) and fossil sources (e.g., coal and natural gas). The cost overruns and time delays for FoaK plants in the United States (and Western Europe) has stymied the deployment of standardized plants, which have the potential to be deployed with substantially lower OCC and LCOE, and with a much shorter construction duration.

The seismic load case is a key contributor to the OCC and LCOE of a new build advanced reactor. The near-surface geology and seismic hazard are different at each power plant site, requiring site-specific geotechnical investigations, probabilistic seismic hazard analyses, seismic soil-structure-interaction analysis, design, engineering, equipment qualification, licensing and regulatory review: all thwarting standardization. To enable deployment of standardized advanced reactors, the cost impact of the seismic load case, and the standardization it prevents, must be minimized. However, before the seismic cost impact can be minimized, it must first be quantified and understood.

Seismic isolation is a proven, mature technology that offers a means to minimize and even eliminate the need for site-specific engineering and review by substantially reducing the horizontal seismic response of structures, systems, and components (SSCs) in a nuclear power plant. The traditional 2D implementation of seismic isolation involves installation of horizontally flexible and vertically stiff isolators (or bearings) at the base of a building (i.e., base isolation). Vertical isolation of buildings and equipment is also viable (IAEA, 2020c). An alternate implementation, to be considered where 2D or 3D base isolation is impractical, is to isolate SSCs and safety-class equipment at their support inside the facility. The conventional implementation would enable standardized plants (i.e., reactor building, its SSCs, and equipment as a package) and the alternate implementation would enable standardized SSCs and safety-class equipment.

Although the benefits of seismically isolating advanced reactors, in terms of reduced seismic demands and risk, are well established (e.g., Tajirian *et al.* (1989), Tajirian (1992), Tajirian and Patel (1993), Clark *et al.* (1995), Aiken *et al.* (2002), Huang *et al.* (2008; 2009; 2011b; 2011a), Kumar *et al.* (2015; 2017a; 2017b), Bolisetti *et al.* (2016), Yu *et al.* (2018)), seismic isolation has yet to be applied to a nuclear power plant in the United States. A decade ago, two key impediments to the implementation of seismic isolation in NPPs were: 1) a lack of technical guidance and standards for analysis and design of seismically isolated NPPs, and its associated regulatory and financial risks, and 2) a lack of data on the financial costs and benefits of seismic isolation.

The first impediment has been addressed. Tools and guidelines for base isolation of nuclear facilities have been developed through research projects funded by the U.S. Department of Energy (DOE) and the U.S. Nuclear Regulatory Commission (NRC). Consensus standards, ASCE/SEI 4-16 (ASCE, 2017) and ASCE/SEI 43-19 (ASCE, 2021), now include chapters specific to seismic isolation. Three technical reports on the analysis and design of seismically isolated nuclear power plants have been published by the NRC: 1) NUREG/CR-7253, Technical considerations for seismic isolation of nuclear facilities (Kammerer *et al.*, 2019), 2) NUREG/CR-7254, Seismic isolation of nuclear power plants using sliding bearings (Kumar *et al.*, 2019a), and 3) NUREG/CR-7255, Seismic isolation of nuclear power plants using elastomeric bearings (Kumar *et al.*, 2019b). Journal articles, conference papers, and technical reports support and complement the standards, with many identified in Whittaker *et al.* (2018). Studies on the seismic isolation of safety-class equipment in NPPs are ongoing at the time of this writing and results will be included in future editions of ASCE 4 and ASCE 43.

This study addresses the second impediment, that is, identifying the financial benefits of seismically isolating NPPs. Unlike other industries, including oil, gas, and petrochemical, there are no modern, non-proprietary data available to engineers that characterize the influence of the seismic load case on the total capital cost of either Generation III or Generation IV (advanced) reactors. Stevenson (1981; 2003) published the last generic dataset, using baseline construction costs from 1970s, and prior to the Three Mile Island (TMI) accident, which triggered a more stringent regulatory environment. See Figure 3, which presents data digitized from Stevenson (1981; 2003). He estimated the increase in OCC for a Generation II large light water reactor (1100 to 1300 MWe) as a function of earthquake shaking intensity, from 0.1 g to 0.6 g peak ground acceleration (PGA). Stevenson binned the OCC into seven categories, and then calculated the cost in each category for a) a baseline design (i.e., no seismic load case), b) design for 0.2 g PGA shaking, and c) design for 0.6 g PGA shaking. This analysis provided three data points in each category. Equations were prepared to compute the percent of OCC associated with the seismic load case as a function of PGA between 0.10 g and 0.60 g. In 1981, the percentage of the total cost attributed to the seismic load case was about 3% at 0.2 g PGA and about 9% at 0.6 g. Stevenson updated these data points in 2003 to be 9% at 0.2 g PGA and 17% at 0.6 g, and assigned the increases to changes in unit cost and escalation of material and labor costs. However, Stevenson did not identify the cost penalty of being unable to reuse a reactor design and to repeat procurement from a qualified supply chain, which would substantially boost the seismic penalty. Stevenson's percentage increases in OCC due to the earthquake load case are substantially smaller than recent anecdotal estimates that are based on analysis of post-TMI construction.

In 2018, nuclear utilities, reactor developers, engineers, and equipment suppliers were polled for cost data. None polled could provide information that could clearly identify the cost impact of the seismic load case. Two reasons were given: 1) modern reactors of one type have not been built at multiple sites with varying seismic hazard, and 2) reactor designs have traditionally targeted a minimum level of earthquake shaking for design (e.g., PGA = 0.3 g) and a baseline configuration, which set aside the seismic load case, did not exist.

To assemble a cost dataset, scheme-level designs were prepared for two fundamentally different advanced reactors. Both reactor buildings were equipped with bespoke pieces of safety-class equipment. The buildings were then analyzed for incremented levels of earthquake shaking to assess the impact of the seismic load case on the safety-class equipment, measured in terms of both vessel weight and horizontal accelerations, which influence equipment internal (e.g., fuel packages) and external (e.g., control rod drives) to the vessel. Analysis results were then used to support a questionnaire that was transmitted to domain experts to quantify the impact of the seismic load case on the capital cost of bespoke safety-class equipment. Results are presented later in this paper.

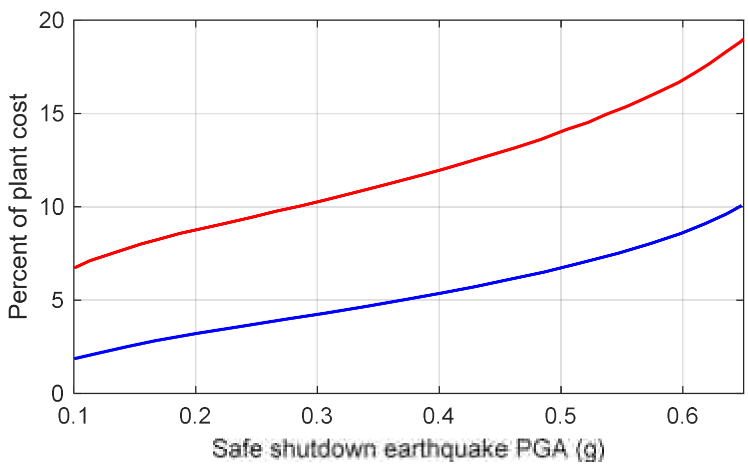


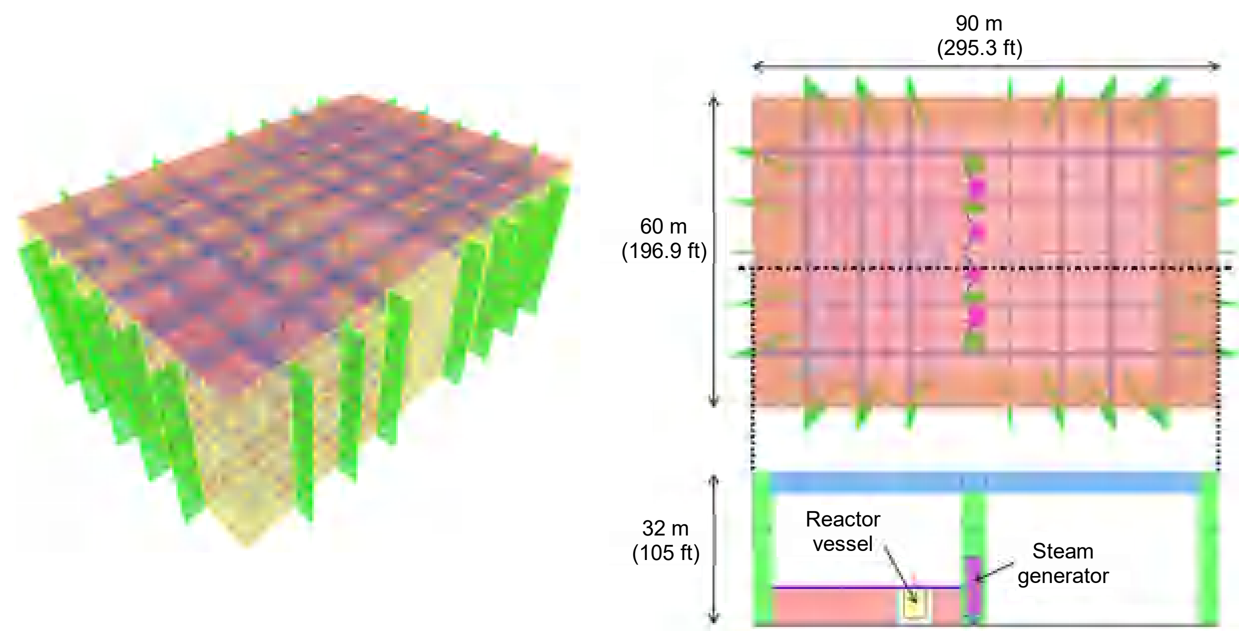
Figure 3. Percentage increase in cost as a function increasing earthquake shaking (adapted from Stevenson (1981; 2003))

2. Characterizing the impact of the seismic load case

Advanced reactor buildings were designed to accommodate a molten chloride fast reactor (MCFR) and a high temperature gas reactor (HTGR). Both reactor buildings were populated with three unique pieces of safety-class equipment: a reactor vessel, a steam generator vessel, and a control rod drive mechanism (CRDM) housing mounted at the head of the reactor vessel. Numerical models of the reactor buildings, including the safety-class equipment were developed in SAP2000 (CSI, 2019). Lal *et al.* (2020) presents the associated numerical modeling and response-history analyses, which is summarized next.

2.1. Reactor buildings and its safety-class equipment

The *generic* MCFR was housed in a two compartment, reinforced concrete building with overall plan dimensions of 90 m (295.3 ft) by 60 m (196.9 ft). The height from the basemat to the top of the roof was 32 m (105 ft). The building frame consisted of perimeter walls and a center wall separating the two compartments. The first compartment had two stories and housed the reactor vessel; the second, one-story compartment housed four steam generator vessels. The reactor vessel (RV1) was supported at its head at the level of the suspended floor in the first compartment. The steam generator vessels (SG1) were supported horizontally and vertically at their base and laterally at their head. The CRDM housing (CRDM1) was welded to the reactor head. Figure 4 presents an isometric view, and plan and cross-section of the building model.

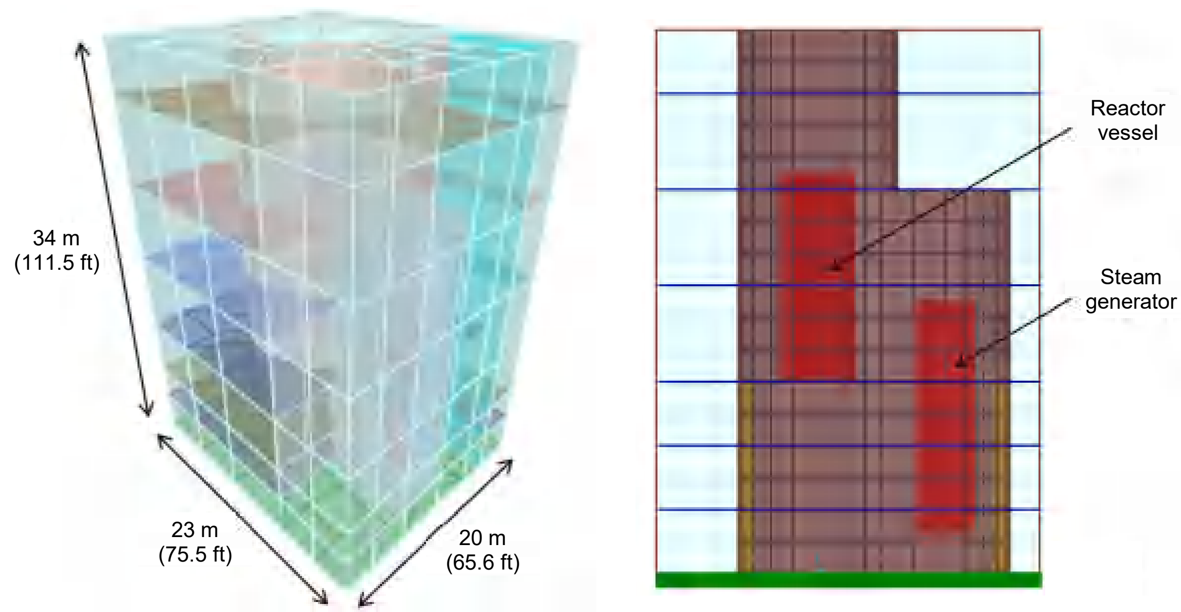


a) isometric view b) plan and cross-section

Figure 4. Numerical model of MCFR building

The *generic* HTGR was housed in a multi-story reinforced building with two citadels, one housing the reactor vessel and the other a steam generator vessel. The plan dimensions of the building were 23 m (75.5 ft) by 20 m (65.6 ft) and the height from the basemat to the top of the roof was 34 m (111.5 ft). The reactor vessel (RV2) was supported at its base, approximately 13 m (42.7 ft) above the basemat. The steam generator vessel (SG2) was supported approximately 5 m (16.4 ft) below its head, at the same level the reactor vessel was supported. The CRDM housing (CRDM2) was attached to the reactor head. Figure 5 presents the isometric view and cross section of the HTGR building model.

Generic designs of the reactor buildings and their safety-class equipment were developed in consultation with the subject matter experts at TerraPower (MCFR) and X-energy (HTGR). Table 1 lists the dimensions of, materials used for, and the assumed internal pressures of the reactor and steam generator vessels in the two reactor buildings.



a) isometric view b) plan and cross-section

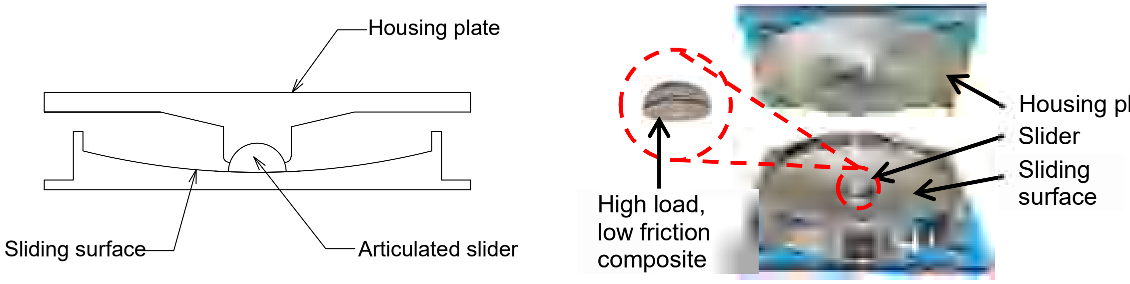
Figure 5. Numerical model of HTGR building

Table 1. Design details of safety-class equipment in reactor buildings

	Reactor vessel		Steam generator		CRDM housing	
	MCFR	HTGR	MCFR	HTGR	MCFR	HTGR
Diameter	5 m (16.4 ft)	4.5 m (14.8 ft)	3 m (9.8 ft)	3.5 m (11.5 ft)	0.25 m (0.8 ft)	0.25 m (0.8 ft)
Height	6 m (19.7 ft)	14 m (45.9 ft)	14 m (45.9 ft)	15.5 m (50.9 ft)	2.5 m (8.2 ft)	2.5 m (8.2 ft)
Material	316 stainless steel	SA 508 low alloy steel	316 stainless steel	SA 516 low alloy steel	316 stainless steel	SA 508 low alloy steel
Internal pressure	0.5 MPa (5 bars)	7 MPa (70 bars)	1 MPa (10 bars)	7 MPa (70 bars)	-	-

2.2. Isolation systems

Single concave Friction Pendulum (FP) bearings were utilized to base isolate the reactor buildings. The single concave FP bearing consists of an articulated slider coated with PTFE-type composite, a sliding surface of polished stainless steel, and a housing plate. Figure 6 shows a cross section and internal construction of a single concave FP bearing. More information on single concave FP bearings is presented in Constantinou *et al.* (2007) and Kumar *et al.* (2019a). The isolators had a sliding period of 3 seconds and the coefficient of sliding friction was assumed to be 0.06—a typical design value. One isolation system was developed for each building and neither was optimized for the analysis herein. The vertical stiffness of the bearings was set to a high value. The MCFR (HTGR) building was isolated using 70 (20) bearings.



a) cross section b) internal construction

Figure 6. Single concave Friction Pendulum bearing

2.3. Reactor building site and response-history analyses

The reactor buildings were assumed to be sited at the Idaho National Laboratory (INL). Yu *et al.* (2018) established a design-basis earthquake (DBE) spectrum at INL for a return period of 10,000 years, with a geomean horizontal peak ground acceleration (PGA) of 0.3 g. To characterize the impact of the seismic load case on the weights and accelerations of the safety-class equipment, ground shaking effects were characterized by a) the shape of the INL spectrum, and b) PGAs with amplitudes of 0.1 g, 0.2 g, 0.3 g and 0.5 g. The thirty sets of two-horizontal-component ground motions generated by Yu *et al.* (2018) were used for response-history analyses of the reactor buildings at each intensity by amplitude scaling the motions. The ground motions were input at the base of the model. Soil-structure-interaction was neglected. Two variants of the reactor buildings were analyzed: fixed-base (conventional) and base-isolated. The effects of vertical earthquake shaking on the responses of the fixed-based and isolated buildings were not calculated but are expected to be similar for a given return period of earthquake shaking. (Horizontal shaking has a much greater effect on the stresses in the walls of the reactor and steam generator vessels, and lateral accelerations of the vessel internals and equipment, than vertical shaking.) The products of the response-history analyses, for each intensity of earthquake shaking, were 1) stresses in the walls of the vessels, 2) peak horizontal accelerations at point of attachment of equipment, and 3) peak horizontal accelerations in the vessels at a representative location (to represent accelerations of the internals), and 4) peak horizontal accelerations at the top of the CRDM housing.

To calculate vessel weight, minimum wall thickness was determined using the allowable design stress intensity per the ASME Boiler and Pressure Vessel Code (ASME, 2017). The earthquake-induced shear stresses in the vessel walls, calculated per ASCE/SEI Standard 4-16, were combined with those from operational loadings per the ASME code to determine the total stress intensity, which was then compared to the allowable value. The wall thickness was increased in increments of 1 mm, to be code compliant, when earthquake shaking produced combined stresses in excess of the allowable value.

2.4. Results of response-history analyses

The design, detailing, and fabrication of safety-class equipment will be affected by the seismic load case. For the reactor and steam generator vessels, an increase in earthquake intensity will require 1) an increase in the thickness of the vessel beyond a threshold intensity of shaking, 2) an increase in anchorage and lateral bracing of the vessel, and 3) lateral bracing and strengthening of the internal equipment, and likely adjustments to the internal dimensions of the vessel, and may require a change in construction method, for example, rolled plate to forged plate.

Table 2 characterizes the weight of reactor and steam generator vessels as a function of increasing earthquake shaking. The weight of the vessels designed for operational loadings only was set equal to 100 to normalize the results, and reported to the nearest 10. Table 3 presents the peak horizontal acceleration at the points of attachment of equipment. Table 4 presents the peak horizontal accelerations at a representative location in the vessels, and at the top of the CRDM housings. Data is provided in each table for the fixed-base and base-isolated reactor buildings.

The *seismic penalty* in the fixed-base reactor buildings is significantly higher than in the base-isolated buildings. In terms of increased vessel weights, the greatest penalty is for SG1 (100 units to 390 units for an increase in PGA from 0.0 g to 0.5 g) and the least for SG2 (100 units to 130 units for an increase in PGA from 0.0 g to 0.5 g). In contrast, only a 40% (SG1) and 10% (SG2) increase in vessel weight is required to resist earthquake shaking of up to 0.5 g PGA in the isolated buildings. From the accelerations reported in Table 4 for the fixed-base buildings, it is evident that the design and fabrication of vessel internals and CRDM housings will pose unique challenges and increase their cost. The corresponding peak horizontal accelerations in the isolated buildings are significantly smaller than those in the fixed-base buildings, with reductions by a factor of between 6 and 18 for a PGA of 0.3 g.

The reduced *seismic penalty* in the base-isolated buildings will enable use of standardized equipment across multiple sites. Consider the data in the open green rectangle in Table 2. For conventional (fixed-base) construction, 20% (RV1), 40% (SG1), 10% (RV2), and 10% (SG2) increases in vessel weight over those required for operational loadings is required for the 0.1 g PGA site. However, these percentage increases in vessel thickness would provide sufficient capacity to resist earthquake shaking with PGA = 0.50 g when the building is isolated. For these examples, seismic isolation would enable deployment of standardized equipment across many sites, leading to drastic reductions in capital cost, as discussed next.

3. Cost study

3.1. Questionnaire

Thirteen questions were developed to quantify of the impact of the seismic load case on the capital cost of safety-class equipment. The questionnaire sought to quantify costs of analysis, design, seismic qualification, regulatory review, and fabrication of FoaK and standardized vessels. The *fixed-base* data of Tables 2, 3, and 4 were attached to the questionnaire. The *isolated* data in the tables was not included in the questionnaire because results could be interpolated from the fixed-base data. Each vendor was provided with a table to enter the cost information, where all costs were normalized by question #4 (=100) to address differences in power rating. The questions were:

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 all costs of analysis, design, seismic qualification, and regulatory review (equal to or greater than the sum of costs 1, 2 and 3).
7. Cost to fabricate the first unit with seismic capacity associated with PGA = 0.1 g. Use the weights and/or accelerations 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 all costs of 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 and/or accelerations 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 all costs of 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 and/or accelerations 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 all costs of 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 and/or accelerations in the tables above to estimate the increased fabrication cost.

The questionnaire did not address the indirect and financing costs associated with the time required to complete the pre-fabrication tasks and the lengthened construction schedule, both of which can be a significant fraction of capital cost per the left bar in Figure 2. The questionnaire was transmitted to 32 domain experts in North America and abroad. Eleven responses were received.

3.2. Cost data

Table 5 presents the averaged values for each piece of equipment and each question, rounded up or down to the nearest multiple of five. Using the data from Table 5, the capital cost of the safety-class equipment can be calculated as a function of increasing earthquake intensity. The capital cost can be separated into engineering cost (i.e., analysis, design, qualification, and regulatory review) and fabrication cost. The engineering costs associated with the first delivery of a piece of equipment, designed for operational loadings only, is the sum of costs 1, 2 and 3 in Table 5. Figure 7 presents the breakdown of capital cost into engineering and fabrication costs, as a function of increasing shaking intensity.

The cost data presented here were developed for *generic* designs of two advanced reactors sited at the INL site. Assumptions were made for the analysis and design of the two reactors buildings and their equipment. Alternate assumptions and choices will lead to different outcomes in terms of vessel weights, accelerations of internals and equipment, and engineering and fabrication costs but the trends are both important and not quantified elsewhere. As such, the data are considered to be indicative of, but not specific to, current or proposed designs of advanced nuclear reactors.

3.3. Cost penalty for fixed-base reactor buildings

The impact of the seismic load case for the fixed-base buildings can be characterized by comparing the FoaK capital cost of the equipment designed for operational loadings and incremented earthquake loadings. See Figure 7. For each piece of equipment and PGA = 0 g, the fabrication cost (cost #4) is normalized to 100. As can be observed from the figure, the seismic penalty for the four vessels, in terms of capital cost, is significant, ranging from about 60% (115%) to 90% (160%) for a PGA of 0.3 g (0.5 g).

Table 2. Normalized weight of reactor vessels and steam generators

PGA (g)	RV1		SG1		RV2		SG2	
	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 3. Peak horizontal acceleration at points of attachment of equipment

	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
RV1	0.16	0.10	0.32	0.12	0.48	0.15	0.80	0.18
CRDM1	0.16	0.10	0.32	0.12	0.48	0.15	0.80	0.18
SG1	0.16	0.10	0.32	0.12	0.48	0.15	0.80	0.18
RV2	0.23	0.09	0.47	0.11	0.67	0.13	1.17	0.15
CRDM2	3.19	0.33	6.38	0.44	9.43	0.51	16.0	0.59
SG2	0.23	0.09	0.47	0.11	0.67	0.13	1.17	0.15

Table 4. Peak horizontal acceleration at representative locations in reactor vessels and steam generators and at the top of the CRDM housings

	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
RV1	0.54	0.20	1.08	0.27	1.62	0.30	2.70	0.37
CRDM1	0.69	0.18	1.39	0.22	2.08	0.24	3.47	0.27
SG1	0.53	0.18	1.05	0.23	1.58	0.26	2.63	0.30
RV2	3.19	0.33	6.38	0.44	9.43	0.51	16.0	0.59
CRDM2	5.82	0.59	11.6	0.85	16.8	0.97	29.1	1.13
SG2	1.33	0.22	2.67	0.29	3.44	0.35	6.67	0.36

Given the significant cost of these pieces of bespoke safety-class equipment, minimizing (or eliminating) the impact of the seismic load case should be a construction goal.

An important observation from Figure 7 is that the engineering cost associated with the delivery of safety-class equipment is a significant fraction of the capital cost of a FoaK unit: ranging between 80% and 120% of FoaK fabrication cost for units designed for operational loadings only, and between 60% and 140% of FoaK fabrication cost for units designed for earthquake shaking. Eliminating engineering cost, which is possible with a standardized design, will drastically reduce total capital cost.

Table 5. Averaged cost data

Cost #	Piece of equipment					
	RV1	CRDM1	SG1	RV2	CRDM2	SG2
1	30	45	35	40	45	35
2	25	50	25	30	45	25
3	30	25	25	25	20	20
4	100	100	100	100	100	100
5	70	60	75	65	60	70
6	115	145	115	115	150	100
7	115	110	120	120	145	110
8	125	155	135	130	165	115
9	130	125	155	145	205	130
10	140	180	150	155	195	135
11	165	150	200	200	280	150
12	160	235	180	220	375	165
13	235	225	300	285	445	230

3.4. Seismic isolation and a pathway to standardized NPPs

Nuclear power plants are designed for a number of natural hazards, including earthquake shaking, flooding, and extreme winds (and the associated missile impact). A standardized design of a reactor building and its safety-class equipment would have to address all of these natural hazards. Below, the focus is on pieces of unique equipment inside the reactor building and the seismic load case. By reducing earthquake demands, seismic isolation enables simpler building construction and equipment supports, reducing the impact of regulatory oversight and construction inspections, noting that the thickness of the building envelope might be dictated by considerations other than earthquake shaking. The reductions in building cost enabled by base isolation are not quantified herein.

The averaged values of fabrication costs 7 and 13 in Table 5 can be used to quantify the (positive) benefit of seismic isolation on FoaK fabrication cost for the four vessels at a PGA = 0.5 g site: RV1: 235 (fixed base) versus 115 (isolated); SG1: 300 (fixed base) versus 120 (isolated); RV2: 285 (fixed base) versus 120 (isolated); SG2: 230 (fixed base) versus 110 (isolated). For these pieces of equipment, the *reduction* in FoaK fabrication cost is between 50% and 60% if seismic isolation is employed.

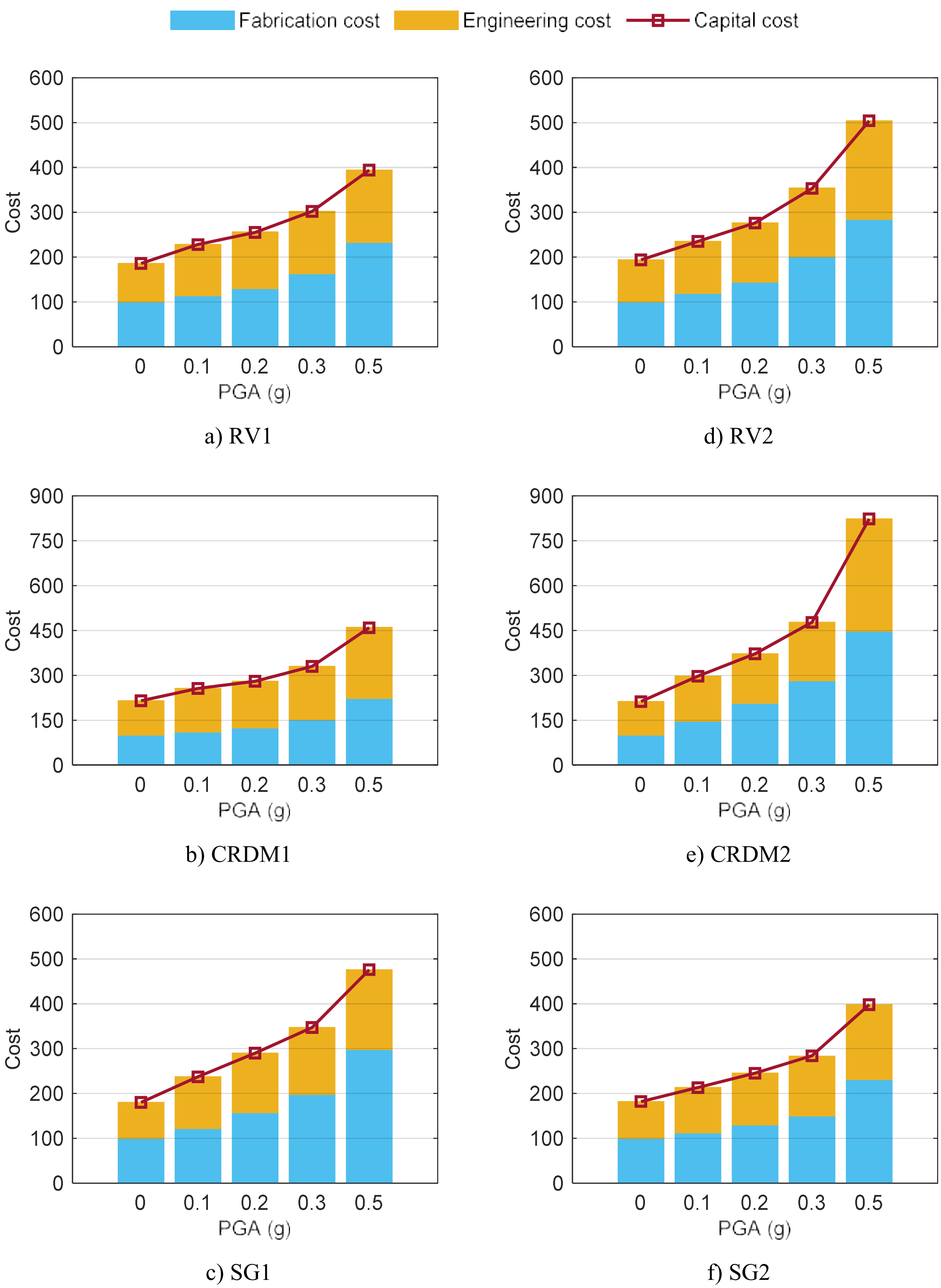


Figure 7. Averaged engineering, fabrication, and capital cost

The corresponding FoaK total capital costs for the four vessels can be compared using costs 6 and 7, and 12 and 13 (or the open red squares in Figure 7), which are – RV1: 395 (fixed base) versus 230 (isolated); SG1: 480 (fixed base) versus 235 (isolated); RV2: 505 (fixed base) versus 235 (isolated); and SG2: 395 (fixed base) versus 210 (isolated). The *reduction* in FoaK total capital cost is between 40% and 50% when seismic isolation is utilized.

As noted previously, a benefit of seismic isolation is that once vessel thickness and/or support fixtures are strengthened (if needed) to provide minimal seismic robustness, no further increase is needed for installation at a site of much higher seismic hazard, enabling standardization of equipment. The seismic isolation system would have to be optimized for the site of higher seismic hazard to limit the seismic demands in structures, systems, and components, including safety-class equipment, to pre-qualified values (e.g., those associated with PGA of 0.1 g in Tables 2, 3, and 4 for the equipment considered herein). Importantly, a standardized design would have to account for increased vertical shaking beyond the baseline unless a 3D isolation system (not considered here) was deployed. If seismic isolation is so implemented, no site-specific analysis, design, qualification, and regulatory review should be required for the isolated, standardized superstructure, systems, and components. Site-specific seismic studies and review would only be needed for the isolation system, the substructure, and safety-related components crossing the isolation interface.

The cost reductions enabled by seismic isolation and standardized equipment can be characterized by comparing the capital cost of FoaK conventional construction and standardized (NoaK) isolated construction. For a PGA = 0.5 g (0.3 g) site, the capital cost of FoaK conventional construction will be the sum of costs 12 and 13 (costs 10 and 11) in Table 5. The capital cost of standardized equipment in a base-isolated reactor building will be a fraction of cost 7, noting that the engineering cost for such equipment should be close to zero. For the averaged cost data of Table 5, the NoaK fabrication cost (cost 5) ranges between 60% and 75% of the FoaK fabrication cost (cost 4). The relative capital costs of the vessels and CRDM housings are presented in Table 6 below, assuming NoaK fabrication cost to be 70% of FoaK fabrication cost. On average, the capital cost of vessels and CRDM housings is reduced by a factor of six (four) for PGA = 0.5 g (= 0.3 g) site. The open headed arrows in Figure 8 identify these reductions.

Utilizing seismic isolation in advanced reactors should lead to substantial savings in cost and time to build. Standardized or NoaK deployment of structures, systems, and components could be achieved, eliminating much of the engineering effort and enabling a streamlined regulatory review and licensing process. By creating order books for many pieces of identical equipment, fabricators of equipment in the nuclear supply chain could then leverage advanced manufacturing technologies, further driving down costs.

Table 6. Capital cost of equipment at PGA = 0.3 g and = 0.5 g sites

	FoaK conventional[1]		NoaK isolated[2]
	0.3 g	0.5 g	
RV1	395	305	81
CRDM1	460	330	77
SG1	480	350	84
RV2	505	355	84
CRDM2	820	475	102
SG2	395	285	77

1. Sum of costs 12 and 13 in Table 5
2. 70% of cost 7 in Table 5

4. Summary and conclusions

One significant impediment to the construction of new NPPs in the United States is the perceived high overnight capital cost (OCC), based in significant part on the cost over-runs and time delays at projects either underway or recently cancelled in the southern United States. The seismic load case is a key contributor to the OCC of a NPP and has stymied the deployment of standardized NPPs. The near-surface geology and seismic hazard is different at each NPP site, requiring site-specific geotechnical investigations, probabilistic seismic hazard analysis, seismic soil-structure-interaction analysis, design, engineering, equipment qualification, licensing, and regulatory review, and effectively rendering reactor construction to be FoaK in every case.

The impact of the seismic load case must be significantly reduced or eliminated to enable standardized designs of advanced reactors. A significant reduction in OCC, perhaps by a factor of four or more, will be needed for commercial customers to consider the construction of advanced nuclear reactors. Reductions in capital cost can only be realized if there is knowledge of how costs accrue for new build nuclear plants but unlike other industries, no modern, non-proprietary data is available at this time, at least in the United States. The last authoritative study on the impact of the seismic load case on the capital cost of NPPs was prepared by Stevenson (1981, 2003) but based on data associated with the construction of Generation II plants in the late 1970s, in a pre-TMI regulatory environment.

To quantify the impact of the seismic load case, two *generic* reactor buildings were designed and each was populated with three pieces of bespoke equipment: a reactor vessel, a steam generator, and a control rod drive mechanism housing. Two variants of each reactor building were developed: fixed base (conventional) and isolated. One isolation system was considered for each reactor building and neither system was optimized. The buildings were sited within the boundary of the Idaho National Laboratory and seismic response-history analysis was performed to generate datasets on vessel wall thicknesses and lateral accelerations, as a function of incremented levels of earthquake shaking.

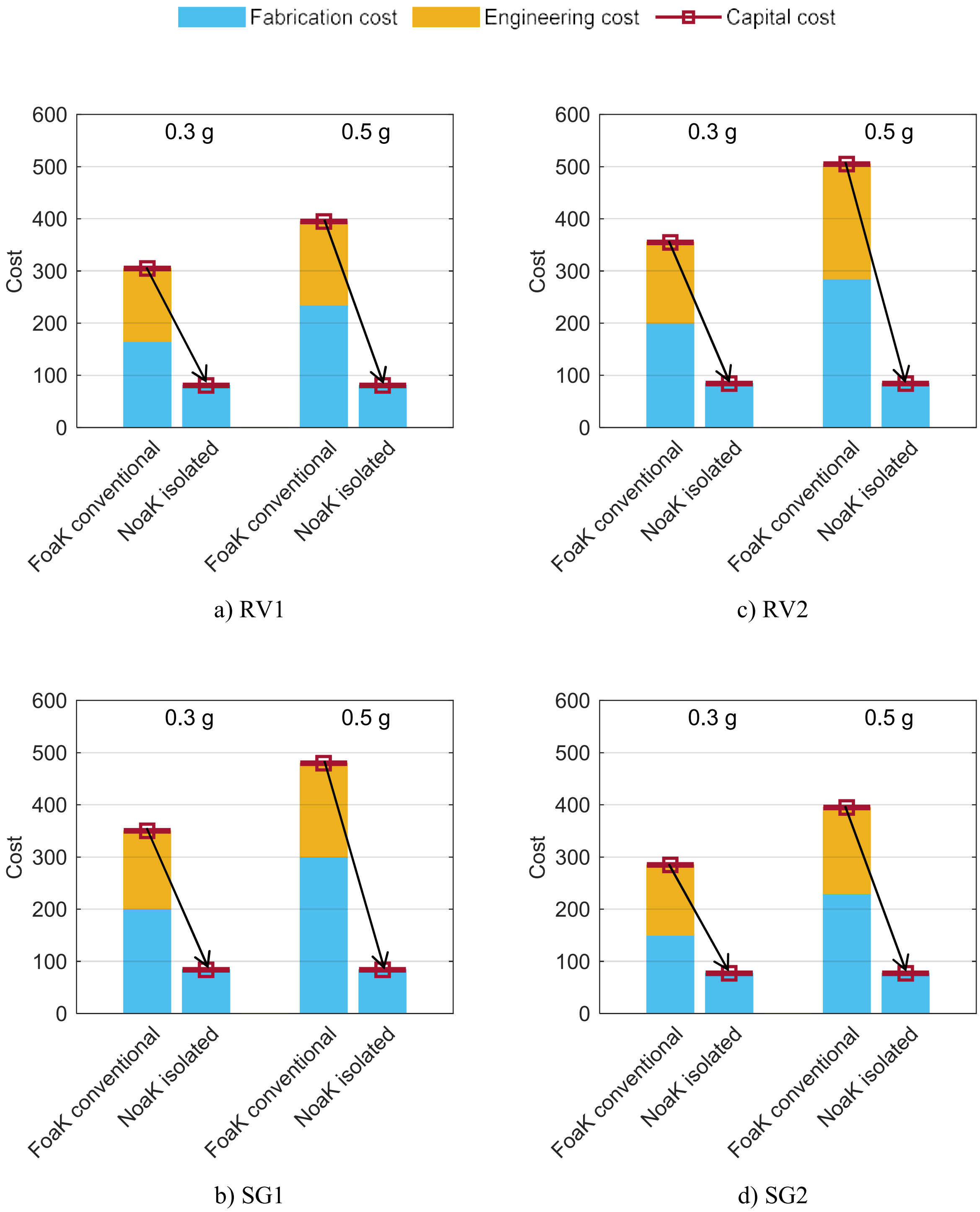


Figure 8. Pathway to standardized safety-class equipment

Analysis results were used to support a cost-related questionnaire that was transmitted to 32 domain experts in the United States and abroad. The questions sought to quantify the costs of analysis, design, seismic qualification, regulatory review, and fabrication of FoaK and standardized (NoaK) equipment as a function of incremented levels of earthquake shaking. Cost data was provided by 11 domain experts and was grouped into engineering (i.e., analysis, design, qualification, and regulatory review) and fabrication costs to characterize a) the impact of the seismic load case on the total capital cost (sum of engineering and fabrication costs) of safety-related equipment, b) reductions in capital cost made possible by seismic isolation, and c) savings associated with standardized construction. Indirect costs were not captured. The key findings of the study are:

1) The seismic load case significantly impacts the capital cost of safety-class equipment.
2) A seismic penalty will be paid for FoaK equipment, with respect to the capital cost of equipment designed for operational loadings only, regardless of whether seismic isolation is employed. The cost penalty will be much smaller if seismic isolation is employed. Importantly, the penalty for seismic isolation is small but constant across sites associated with a wide range of seismic hazard.
3) Engineering costs represent a significant fraction of the total capital cost of FoaK safety-class equipment.
4) A 40% to 50% reduction in FoaK total capital cost of equipment is enabled by seismic isolation.
5) Standardization of equipment is made possible by seismic isolation.
6) The possible reduction to NoaK capital cost of equipment, enabled by seismic isolation, from the benchmark cost associated with conventional construction, could be by a factor of five (and more).

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