Transactions of the SMiRT 27
Yokohama, Japan, March 3-8, 2024
Division V

LIMITING THE IMPACT OF THE SEISMIC LOAD CASE ON A HORIZONTALLY CONFIGURED HTGR

Sai Sharath Parsi[1], Enrique Velez[2], William R. Stewart[2], Koroush Shirvan[3], and Andrew S. Whittaker[4]

[1] Ph.D. Student, Department of Civil, Structural, and Environmental Engineering, University at Buffalo, State University of New York, Buffalo, NY, USA (saishara@buffalo.edu)
[2] Co-founder, Boston Atomics LLC, Boston, MA, USA
[3] Professor, Department of Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA
[4] SUNY Distinguished Professor, Department of Civil, Structural, and Environmental Engineering, University at Buffalo, State University of New York, Buffalo, NY, USA

ABSTRACT

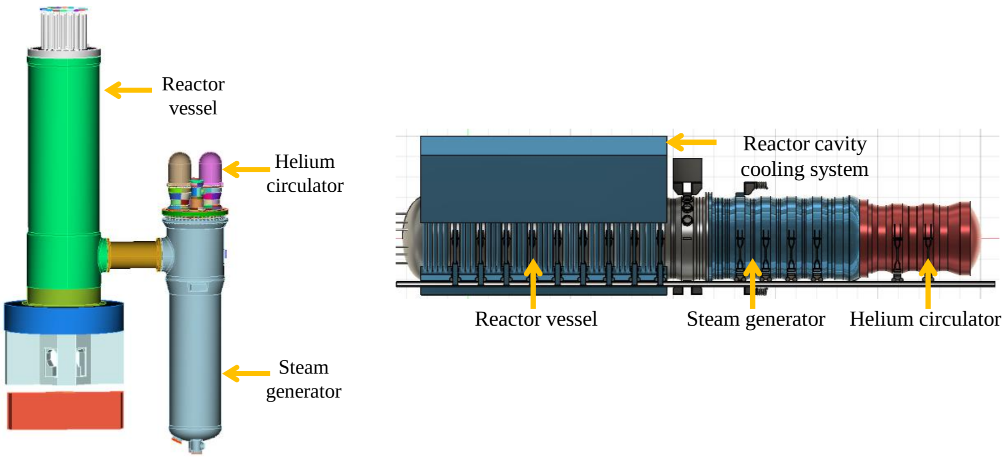
The United States Department of Energy is funding the conceptual development of a horizontally configured high temperature gas reactor (HC-HTGR) under its Advanced Research Demonstration Program (ARDP). Unlike traditional HTGRs, the HC-HTGR design integrates key reactor components, including the reactor vessel, steam generator, and helium circulator, into a single horizontal unit. The horizontal configuration offers several advantages, including a significant reduction in the volume of civil materials (e.g., concrete, steel) and a much smaller overall height for the reactor building. The re-orientation of the reactor components, from vertical to horizontal, necessitates analysis, design, and optimization studies that are being supported by ARDP. This paper focuses on structural engineering aspects of the HC-HTGR, advancing its design by evaluating the seismic robustness of the reactor building, integrated reactor primary system, and critical internals, and devising effective strategies to mitigate the impact of the seismic load case. Analysis results presented in this paper directly support progression of the HC-HTGR design and facilitate future licensing.

1. INTRODUCTION

Future *green* energy systems must generate electricity to power homes, businesses, and industry, and high-temperature heat essential for important industrial processes, including those in steel and petrochemical plants, and paper and pulp production. High-temperature gas reactors (HTGRs) can efficiently deliver both electricity and process heat, but questions remain about their capital cost, attached to a reactor building height of 60+ m and a relatively low power density. Several design features contribute to the height and volume of HTGR buildings, including: (i) a number of HTGRs, such as the US MHTGR, the German AVR, the Japanese HTTR, and the Chinese HTR-10, employ a vertically oriented reactor configuration, (ii) a tall and slender design for the reactor pressure vessel (RV), generally installed 10s of meters above the basemat, (iii) the placement of a tall, slender steam generator (SG) below the level of the RV, (iv) large and thick reinforced concrete walls surrounding the RV and the SG for radiation shielding, and (v) an overhead crane installed above the RV for equipment handling and maintenance. The resulting power density (i.e., power output per unit volume/weight of the building) for such buildings may be too low for commercial viability. For example, the Chinese HTR-PM design (Zhang *et al.*, 2016) showcases twin 110 MWe reactors with a reactor building power density of approximately 2 kWe/m^3. In contrast, the power density of the Westinghouse AP1000 large light water reactor building (Schulz, 2006) is approximately six times greater.

Recognizing the need to drastically increase power density and achieve commercial viability for HTGRs, Boston Atomics, a Boston-based nuclear start-up, has proposed a radical change to the reactor configuration (Stewart *et al.*, 2021): the Horizontally-Configured, modular, High Temperature Gas Reactor

(HC-HTGR). Unlike the traditional vertical configuration of Figure 1a, the HC-HTGR design integrates key reactor components, including the reactor vessel, steam generator, and helium circulator, into a single horizontal unit, as shown in Figure 1b. The re-orientation of the reactor, from vertical to horizontal, significantly reduces the height of the reactor building, eliminates the need for an overhead (or polar) crane for equipment handling and maintenance, and promises higher power density. Preliminary studies have indicated that the power density of the HC-HTGR is 3+ higher than traditionally configured HTGRs, reducing capital cost by at least 20% (Stewart *et al.*, 2021).



a) generic vertical HTGR   b) HC-HTGR (Boston Atomics, 2021)

Figure 1. Vertically and horizontal high temperature gas reactor

The U.S. Department of Energy is funding the conceptual development of the HC-HTGR as a part of its Advanced Reactor Demonstration Program (ARDP), through an Advanced Reactor Concept (ARC-20) project being led by MIT. The three-year (2021-2024) project is a first-of-a-kind collaboration of nuclear, mechanical, and civil engineers. This paper, one product of the ARC-20 project, is advancing the HC-HTGR design by evaluating the seismic response of the reactor building and its integrated reactor primary system. The HC-HTGR design will continue to evolve in the coming years, incorporating feedback from each discipline in a timely, integrated manner. Consequently, the structures, systems, and components in future versions of the HC-HTGR might vary significantly from that presented in this paper. Section 2 describes the physical dimensions, materials, and construction details of the HC-HTGR as of year 2021, including the site assumed for seismic analysis at the beginning of the ARC-20 project. Section 3 presents details of the numerical modeling and the dynamic (modal) characteristics of building and the integrated reactor system. Section 4 presents results of the seismic response-history analyses and characterizes the impact of the seismic load case on the HC-HTGR building and equipment.

2. DESCRIPTION OF THE HORIZONTALLY CONFIGURED HTGR

2.1 Reactor building

The 2021 HC-HTGR building is a reinforced concrete (RC) structure, 10 m tall, with plan dimensions of 75 m $\times$ 14 m. The building is parsed into six major compartments as shown in Figure 2:

- entry and business operations (shaded red): 15 m long and 5 m wide
- control and backup power systems (shaded yellow): 14 m long and 5 m wide
- storage of fresh and spent fuel (shaded purple): 46 m long and 5 m wide
- reactor maintenance (shaded sheen green): 15 m long and 9 m wide
- refueling unit and control drum assembly (shaded orange): 27 m long and 9 m wide
- primary system and reactor cavity cooling system (shaded grey): 33 m long and 9 m wide

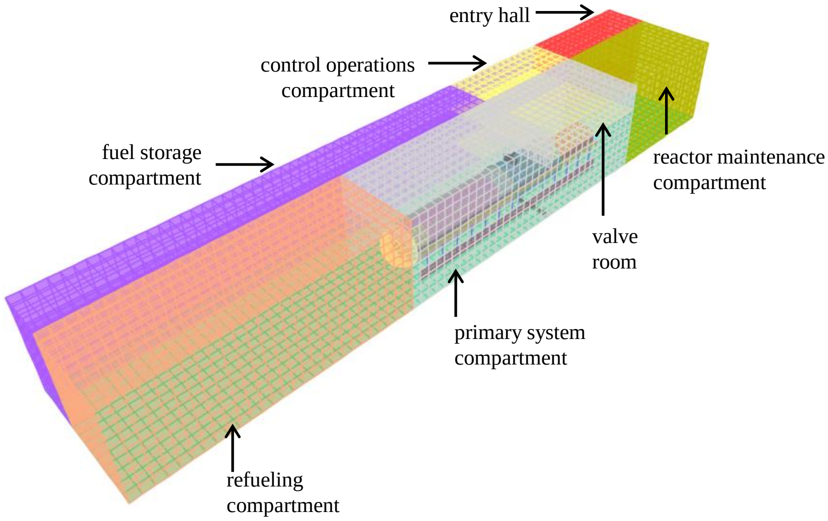


Figure 2. HC-HTGR reactor building, 2021

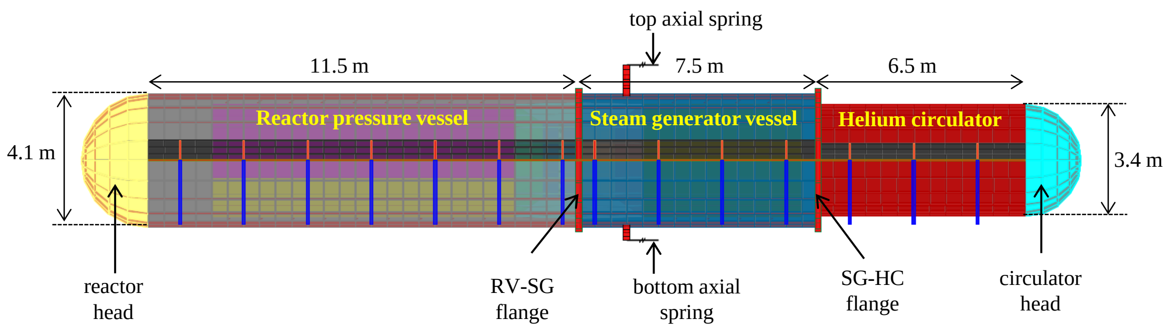
The entry hall, control system, and fuel storage compartments are multistorey, whereas the refueling and reactor maintenance compartments are single-story spaces. The compartment above the reactor primary system has a floor slab, 7 m above the basemat, and it houses the reactor cavity cooling system (RCCS) and valve assemblies for the steam generator. Based on preliminary radiation shielding calculations (Anna and Shirvan, 2023), the perimeter reinforced concrete walls adjacent to the primary compartment are 1.2-m (4-ft) thick. The remaining perimeter walls are 0.75-m (2.5-ft) thick. The interior walls and floor slabs are 0.45-m (1.5-ft) thick and the basemat is 1.2-m (4-ft) thick.

The key structures, systems, and components (SSCs) included in the HC-HTGR building are: the reactor primary system weighing approximately 830 tons, the refueling and control assembly (400 tons, refueling compartment), the reactor cavity cooling system (400 tons, primary compartment), the spent fuel storage (250 tons, floor 1 of the fuel storage compartment), fresh fuel storage (150 tons, floor 2 of the fuel storage compartment), and the reactor maintenance equipment (100 tons, maintenance compartment). For the preliminary analysis reported in this paper, only the reactor primary system is explicitly modeled. Masses are appropriately distributed on the basemat and floor slabs for the remaining SSCs.

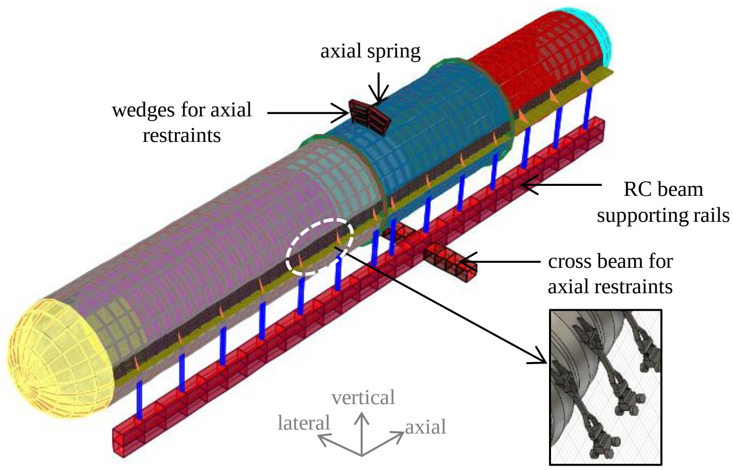
2.2 Reactor primary system

The HC-HTGR primary system integrates key nuclear components (reactor vessel[1], steam generator[2], and heat circulator[3]) in a horizontal alignment, as shown in Figure 3a. The reactor vessel (RV) is a 13.5-m long cylinder, 4.1 m in diameter, with a hemispherical head at one end and a flanged connection to the steam generator at the other. The steam generator (SG) is a 7.5-m long cylinder, 4.1 m in diameter (same as the RV), with flanged connections at both the ends. The helium circulator (HC) vessel is 3.4 m in diameter and 6.5-m long, with a hemispherical head at one end and flanged connection to the steam generator at the other. The flanges at the RV-SG (SG-HC) interface are 200-mm (200-mm) thick and 450-mm (750-mm) wide. The total length of the primary system, including the hemispherical ends, is approximately 31.2 m (102 ft). The wall thickness for all three vessels (RV, SG, and HC) is 110 mm. The design of the RCCS is not sufficiently mature to be modeled explicitly now.

[1] The reactor vessel encloses the reactor core (fuel elements and the moderator) and serves as a pressure boundary to the high-pressure helium coolant used in the HTGR
[2] The steam generator transfers heat from the high-temperature helium coolant to a secondary loop converting water into steam.
[3] The helium circulator controls circulation of the helium coolant through the reactor core to absorb heat generated from nuclear fission.



a) side view (extruded) of the representative numerical model



b) 3D view (extruded) of the representative numerical model

Figure 3. HC-HTGR primary system, 2021

As seen in Figure 3b, the integrated reactor primary system is supported on 28 vertical elements, 14 on each side, and at a 2-m spacing. Each support element is 2 m tall, weighs 0.5 ton (including insulation), and is connected to the primary vessel via a gusset. The support fixture includes a fork piece, adjustable unit, and a roller, as shown in Figure 3b. The rollers slide on rails enabling horizontal movement of the primary system for maintenance, which are in turn supported on beams. Two wedges protrude from the steam generator vessel, at the top and bottom, and support heavy-duty springs that provide axial resistance to the primary system (see Figure 3a). The top axial spring is connected to the roof via a beam near the valve room. A cross beam provides a load path from the bottom axial spring to the basemat.

2.3 Primary system internals

Figure 4 is a three-dimensional view of the primary-system internals, and it includes (a) core barrel, (b) steam generator barrel, (c) support skirts, (d) flanges, (e) cross vessel, and (f) support fingers. The core barrel (CB) is a 11.5-m long, 50-mm thick, multipart component constructed of Alloy 617. It consists of a uniform cylindrical segment, 9.5-m long and 3.5 m in diameter, and a conical (< 5°) flanged skirt. The steam generator barrel (SB) is a 5-m long uniform cylinder, with wall thickness and diameter identical to those of the CB. The cross-vessel assembly connecting CB and SB is a multipart component comprising of conical sections and uniform cylinders with interconnecting bellows to accommodate thermal (axial) expansions. Other internals including the core graphite (reflector and fuel elements), radiation shield material, control assembly, tubes, and plates, are not explicitly modeled but their masses are appropriately distributed on the adjacent elements in dynamic analysis to account for the inertial effects.

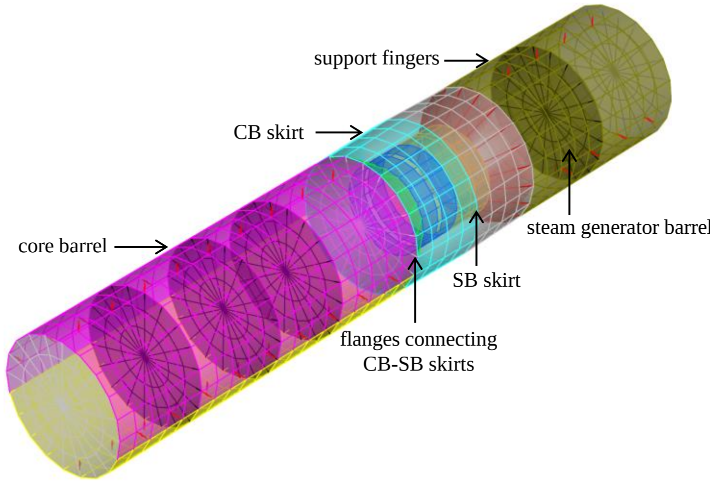
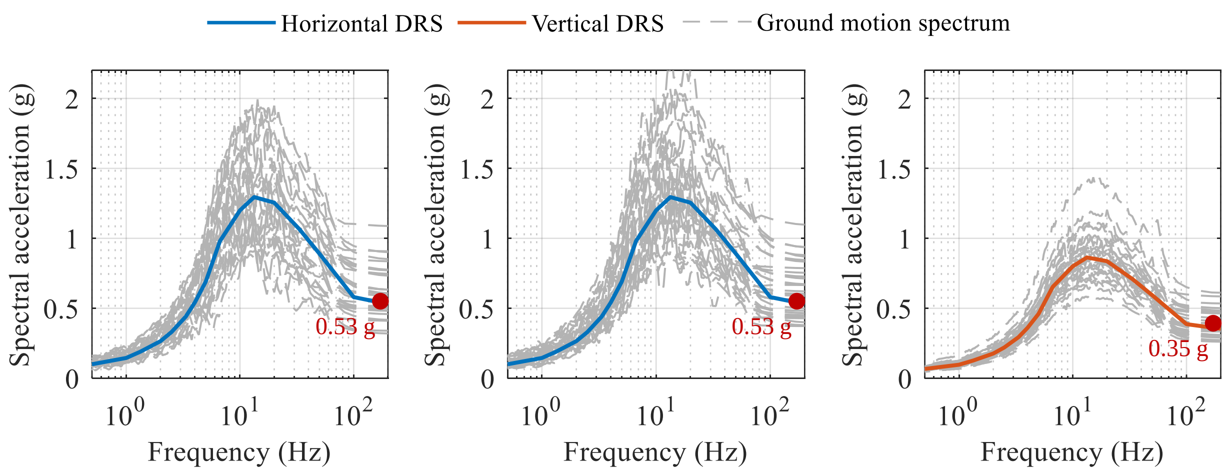


Figure 4. HC-HTGR primary system internals, 2021

2.4 Site conditions and seismic hazard characterization

The choice of a target performance goal (or seismic design category) for the reactor building and its SSCs will require development of a safety case for the HC-HTGR. To facilitate preliminary seismic analysis, and in the absence of a safety case, the HC-HTGR was assigned to seismic design category (SDC) 4 per ANS 2.26 (ANSI/ANS, 2017) and ASCE/SEI 43-19 (ASCE, 2021) with a target performance goal of 4×10^{-5} = 1/25,000. This decision was made on the basis that the volume of material at risk in the HC-HTGR is substantially smaller than in a gigawatt large light water reactor, which is typically assigned to SDC 5. The reactor building was sited at the East Tennessee Technology Park (ETTP) in Clinch River, TN – a site of moderate seismicity in the Central and Eastern United States. Yu *et al.* (2023) characterized the seismic hazard at the ETTP in terms of a design response spectrum (DRS) corresponding to SDC 4. Figure 5 presents the target DRS in the horizontal (solid blue line) and the vertical (solid orange line) directions.



a) horizontal, H1, B/C   b) horizontal, H2, B/C   c) vertical, V, B/C

Figure 5. Target DRS and ground motion spectra, SDC 4, geomean horizontal and vertical shaking, V/H=0.67, ETTP site, site class B/C, 5% damping

Two site classes, namely, B/C and C/D, were considered to represent a wide range of seismic inputs (i.e., near surface geological conditions) to the building. The B/C site class, with a shear wave velocity of 760 m/s in the upper 30 m of the soil column, represents soft rock to dense soil per ASCE 7-22 (ASCE, 2022). The C/D site class represent moderately stiff soil and is associated with a shear wave velocity in the upper 30 m of the soil column of 360 m/s. Only site class B/C results are presented and discussed in this paper. Figure 5 also presents thirty sets of three-component ground motions, as identified by dashed grey lines, that are selected (from PEER NGA-West ground motion database) and scaled to be consistent with the target horizontal and vertical DRS. Additional details on the hazard characterization, ground-motion selection and scaling, and the random orientations of the inputs are presented in Yu *et al.* (2023).

2.5 Seismic isolation systems

The preliminary seismic analysis results reported in this paper considers two base configurations for the HC-HTGR building: conventionally founded and seismically isolated. Multiple seismic isolation systems are being considered but sample results are presented in this paper for two fundamentally different systems: (1) a 3D isolation system using spring isolators and viscoelastic dampers, and (2) a 2D isolation system using single concave Friction Pendulum isolators. Figure 6 presents the assumed layout for the two isolation systems for the HC-HTGR building, neither of which was optimized because the design of the superstructure and safety-related systems is not yet sufficiently mature. The mechanical properties (i.e., spring stiffnesses and viscous damping coefficient) for the 3D isolation system are selected to achieve a target horizontal frequency of 0.9 Hz, a horizontal damping ratio of 25% of critical, a vertical frequency of 2.5 Hz, and a vertical damping ratio of 8% of critical. The 2D Friction Pendulum isolation system properties are selected to achieve a coefficient of friction of 0.05, and a post-elastic (or sliding) period of 3 sec.

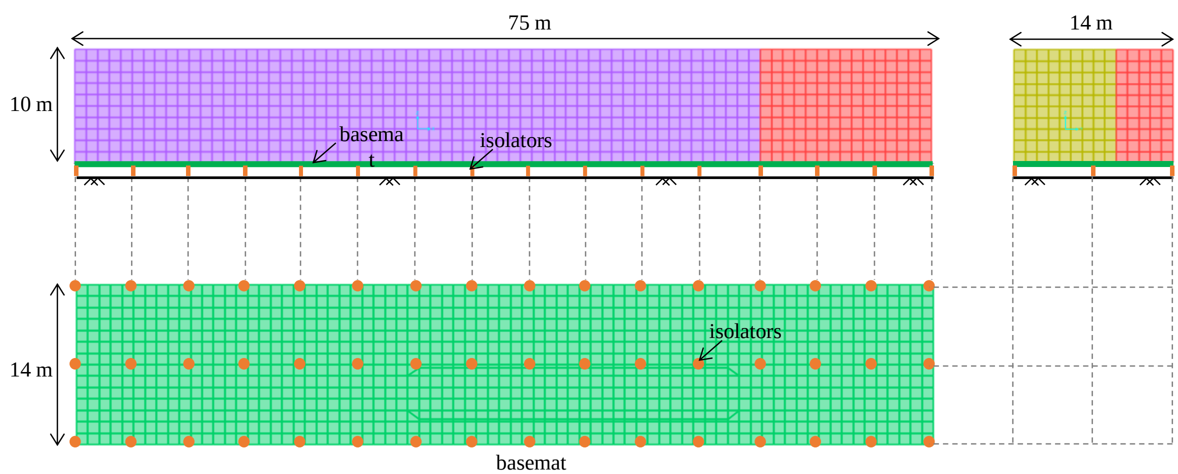


Figure 6. Isolation-system layout for the HC-HTGR building, 2021

3. NUMERICAL MODELING AND DYNAMIC CHARACTERISTICS OF HTGR

3.1 Numerical modeling in SAP2000

A preliminary numerical model of the HC-HTGR building, equipped with the integrated reactor primary system and internals, was developed in the commercial finite element program SAP2000 (CSI, 2023). The numerical model enables (a) identify key modes and frequencies of the reactor building, primary system, and internals, (b) preliminary seismic analysis to characterize the impact of the seismic load case on the building and equipment, (c) dataset generation (e.g., accelerations, displacements) for developing design spaces (Parsi *et al.*, 2020) for the primary system, and (d) assess the benefits of using seismic base isolation in terms of reduction in acceleration demands.

The reinforced concrete walls, basemat, floor slabs, and the roof elements are modeled using four-node shell elements using centreline dimensions. A mesh sensitivity study was performed to determine an appropriate mesh size for the finite elements. Concrete is assumed to be uncracked with a uniaxial compressive strength of 40 MPa. The density, Poisson's ratio, and modulus of elasticity of concrete are assumed as 2400 kg/m^3, 0.2, and 27 GPa, respectively. The primary vessels (RV, SG, and HC), and internals (e.g., core barrel, steam generator barrel, support skirts, flanges) are modeled using four-node shell elements. The primary vessels are assumed to be fabricated from SA 516 Gr 70 steel; the core barrel and cross vessel are assumed to be fabricated from Alloy 617. The densities of the two alloys are 8350 and 7850 kg/m^3, respectively. A Poisson's ratio of 0.3 was used for the steel components and the modulus of elasticity was adjusted for operating temperature. As discussed in Section 2, only the reactor primary system and some of its internals (whose dynamics are presumed important to advance the design (e.g., core barrel)) are explicitly modeled. The inertia (or weight) of the remaining SSCs in the reactor building (e.g., RCCS) and internals in the primary system (e.g., core graphite) was indirectly accounted by distributing their masses on the connecting elements per Figure 7.

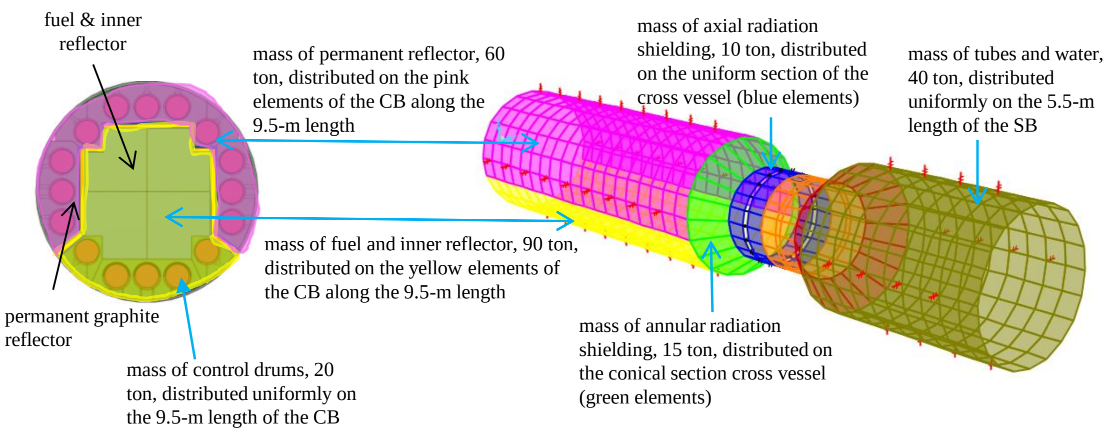


Figure 7. HC-HTGR primary system internals with distributed masses, 2021

The nodes on the building basemat were restrained in all three translational directions. The supports to the primary system (see Figure 3), which include a support plate, fork pieces, adjustable unit, and a roller, were modeled as two-node beam elements with an effective vertical stiffness of 6000 MN/m. The shear and flexural stiffnesses of the elements were assumed equivalent to that of a 0.01 m^2 area steel cross section. The axial springs, at the top and bottom of the steam generator vessel, were modeled as linear elastic springs and assigned an axial (shear) stiffness of 40 MN/m (5 MN/m). The core barrel is connected to the reactor vessel using sets of 4 support fingers placed 90° apart, and at a 1-m spacing along the length of the barrel. Both the 3D and 2D isolators were modeled as two-node link elements with six degrees of freedom (three translational and three rotational) defined at each node.

3.2 Modal frequencies and shapes

Eigen analysis was performed for the HC-HTGR to identify the important modal frequencies for the reactor building and primary system. The first 200 eigenmodes recovered 84%, 92%, and 61% of the mass in the axial (H1), lateral (H2), and vertical (V), respectively. For the reactor building, the dominant modes in the H1 and H2 directions are at 30+ Hz and 7.5 Hz, respectively, with mass participation of approximately 64% and 70%, respectively. In the vertical direction, the mass participation was distributed across several modes (both for the building and the primary equipment), and well-defined vertical frequencies could not be identified. For the primary system, the dominant modes in the H2 direction are observed at frequencies of 1.2 Hz and 1.6 Hz, respectively. The two modes include translational and torsional responses and recover nearly 95% of the mass of the primary system. The dominant translation mode in the H1 direction is at 1.9 Hz, with mass participation greater than 95%. In the vertical direction, the response of the primary system is dominated by multiple modes in the frequency range from 15 to 35 Hz.

4. SEISMIC RESPONSE HISTORY ANALYSIS AND RESULTS

Seismic response-history analysis is performed for the fixed-base and the base-isolated variants of the HC-HTGR building using the earthquake motions for the ETTP site. The thirty ground motion triplets of Figure 5 are applied along the principal axes of the building. The products of the response-history analyses are the horizontal and vertical accelerations (and relative displacements) at points of interest defined in Table 1.

Table 1. Locations to monitor seismic responses for the HC-HTGR

Building	*Primary vessels*	*Internals*
#p1 – seismic input	#p7 – reactor head[a]	#p11 – core barrel[b]
#p2 – basemat[c]	#p8 – RV-SG flange[d]	#p12 – steam generator barrel[e]
#p3 – fresh fuel room	#p9 – SG-HC flange	#p13 – cross vessel
#p4 – RCCS room[f]	#p10 – circulator head	
#p5 – roof center		

[a]Representative of the seismic input to the head-mounted oscillators such as control drum/rod extensions.
[b]Representative of the seismic input to the reflector- and fuel-block assembly inside the core barrel.
[c]In the isolated building, the earthquake shaking at the basemat, #p2, is filtered through seismic isolators and is different from the seismic input, #p1. In the fixed-base configuration, #p1 and #p2 are however identical. Point #p2 is representative of seismic input to the refueling equipment.
[d]Representative of the seismic input at the point of attachment of the core barrel and steam generator barrel.
[e]Representative of the seismic input to tubes, plates, and other internals attached to the SB walls.
[f]Representative of the seismic input to the reactor cavity cooling system.

Table 2 presents the mean (of 30 ground motions) maximum geomean-horizontal and vertical accelerations in the HC-HTGR building for site class B/C. The values are reported for the fixed-base (FB), and the 2D and 3D base-isolated configurations. The use of 3D base isolation enabled a significant reduction in both the horizontal (factor between 5 and 13) and vertical (factor between 2 and 8) accelerations in the reactor building compared with those in the fixed-base building. Importantly, the acceleration demands along the height of the building are nearly uniform (i.e., no amplification), an outcome that is impossible to achieve using fixed-base construction. The peak geomean horizontal accelerations using 2D isolation system are 4 to 8 times smaller than those in the fixed-base counterpart. The vertical accelerations, however, are increased by 10 to 15%, which can be mitigated by optimizing the layout and properties of the 2D isolation system. The percentage reductions in horizontal response for the 2D and 3D systems might appear to be counter intuitive. However, for this combination of site, soil class, building, equipment properties and isolator properties, and isolator layout, the deployment of the more heavily damped, 0.9 Hz 25%-damped 3D isolation system produces larger reductions in response than the 3-sec 2D bilinear isolation system. Different outcomes would be achieved by adding damping to the 2D isolation system or by adjusting its stiffness and damping in the vertical direction.

Table 2. Mean maximum accelerations (g) in the HC-HTGR building

	Geomean horizontal				Vertical		
	FB	BI-2D	BI-3D		FB	BI-2D	BI-3D
#p1	0.53	0.53	0.53		0.35	0.35	0.35
#p2	0.53	0.13 (↓ factor 4)	0.11 (↓ factor 5)		0.35	0.40 (↑ 13%)	0.21 (↓ factor of 2)
#p3	0.86	0.17 (↓ factor 5)	0.11 (↓ factor 8)		0.85	0.95 (↑ 10%)	0.21 (↓ factor of 4)
#p4	1.27	0.15 (↓ factor 8)	0.11 (↓ factor 11)		1.14	1.31 (↑ 15%)	0.21 (↓ factor of 6)
#p5	1.48	0.16 (↓ factor 9)	0.12 (↓ factor 13)		1.57	1.72 (↑ 10%)	0.21 (↓ factor of 8)

Table 3 present the mean maximum geomean horizontal and vertical accelerations in the primary system and internals. For the considered 3D isolation system, the horizontal accelerations at selected locations in the primary system are reduced by up to 50% (i.e., factor of 2) compared with those in the fixed-base building. Much greater reductions, up to 85% (i.e., factor of 6), are achieved in the vertical direction. Use of 3D isolation resulted in similar acceleration demands along the axis of the primary system (see points #p7 through #p10), which greatly simplifies the design and qualification of reactor internals.

Table 3. Mean maximum accelerations (g) in the HC-HTGR primary system

	Geomean horizontal				Vertical		
	FB	BI-2D	BI-3D		FB	BI-2D	BI-3D
#p7	0.40	0.35 (↓ 13%)	0.25 (↓ 38%)		1.65	1.95 (↑ 18%)	0.27 (↓ 84%)
#p8	0.32	0.27 (↓ 16%)	0.21 (↓ 35%)		0.80	0.95 (↑ 19%)	0.26 (↓ 68%)
#p9	0.40	0.30 (↓ 25%)	0.22 (↓ 45%)		0.80	0.88 (↑ 10%)	0.25 (↓ 69%)
#p10	0.51	0.43 (↓ 16%)	0.25 (↓ 50%)		1.61	1.87 (↑ 16%)	0.26 (↓ 84%)
#p11	0.35	0.34 (similar)	0.24 (↓ 31%)		1.41	1.71 (↑ 21%)	0.27 (↓ 81%)
#p12	0.37	0.28 (↓ 24%)	0.22 (↓ 40%)		0.79	0.92 (↑ 16%)	0.25 (↓ 69%)
#p13	0.33	0.25 (↓ 25%)	0.20 (↓ 40%)		1.02	1.22 (↑ 19%)	0.26 (↓ 75%)

Table 4 presents mean maximum displacements (relative to the basemat) at representative locations on the primary system and internals, #p7 through p#13. The vertical displacements at the selected locations are negligible (< 3 mm) and are not reported in the table. The horizontal (axial and lateral) displacements are large in all three configurations (fixed base, 2D and 3D isolation): approximately 50 mm at the ends of the primary system. These large displacements are attributed to the low horizontal stiffness of the primary system and likely would make qualification of the vertical supports, interconnecting pipelines, and safety-related umbilical lines challenging. Practical solutions to increase the lateral and axial stiffness of the primary system, and subsequently to reduce the seismic-induced displacements, are being developed. Once the designs of the primary system, internals, and the safety-related umbilical lines have been optimized for operational loadings, a seismic design space will be characterized by identifying limiting values of acceleration and displacement that could be sustained by the operationally optimized equipment. The primary system supports, and the base isolation system will then be designed to limit the accelerations, velocities, and displacements to this design space, and this is work underway.

Table 4. Mean maximum relative horizontal displacements (mm) in the HC-HTGR primary system

	Axial (H1)			Lateral (H2)		
	FB	BI-2D	BI-3D	FB	BI-2D	BI-3D
#p7 – reactor head	26	19	14	53	44	56
#p8 – RV-SG flange	26	19	14	32	25	32
#p9 – SG-HC flange	26	19	14	39	32	27
#p10 – circulator head	26	19	14	58	48	34
#p11 – core barrel	26	19	14	45	38	49
#p12 – SG barrel	26	19	14	37	31	27
#p13 – cross vessel	26	19	14	32	25	30

ACKNOWLEDGEMENTS

The study described in this paper was funded by the U.S. Department of Energy under its Advanced Reactor Concept (ARC-20) project, Award Number DE-NE0009049. Boston Atomics provided the physical dimensions, geometry, and details of the construction materials assumed herein for the HC-HTGR reactor building and its primary system structures as input to the project at its inception. The views and opinions of the authors expressed herein do not necessarily state or reflect those of the United States Government, University at Buffalo, Massachusetts Institute of Technology, Boston Atomics LLC, or any agency thereof.

REFERENCES

Anna, K., and Shirvan, K. (2023). "Activation and radiation damage analysis of steel and reinforced concrete components in HC-HTGR." Internal Presentation to DOE, Massachusetts Institute of Technology, Cambridge, MA.

American National Standards Institute/Americal Nuclear Society (ANSI/ANS). (2017). "Categorization of nuclear facility structures, systems, and components for seismic design." *ANSI/ANS 2.26-2004 (R2017)*, Washington D.C.

American Society of Civil Engineers (ASCE). (2021). "Seismic design criteria for structures, systems, and components in nuclear facilities." *ASCE/SEI 43–19*, Reston, VA.

American Society of Civil Engineers (ASCE). (2022). "Minimum design loads for buildings and other structures." *ASCE 7–22*, Reston, VA.

Computers and Structures Inc (CSI). (2023). "Computer Program SAP2000 (Version 25)." Berkeley, CA.

Parsi, S. S., Lal, K. M., Shirvan, K., Kosbab, B., Cohen, M., Kirchman, P., and Whittaker, A. S. (2020). "Equipment-level seismic protective systems for advanced nuclear reactors." *Proceedings: 17th World Conference on Earthquake Engineering (17WCEE)*, September 2020, Sendai, Japan.

Schulz, T. L. (2006). "Westinghouse AP1000 advanced passive plant." *Nuclear Engineering and Design*, 236(14), 1547-1557.

Stewart, W. R., Velez-Lopez, E., Wiser, R., and Shirvan, K. (2021). "Economic solution for low carbon process heat: A horizontal, compact high temperature gas reactor." *Applied Energy*, 304(117650).

Yu, C. C., Mir, F. U. H., Carmichael, B. M., Chisholm, B. M., Redd, J., Bolisetti, C., and Whittaker, A. S. (2023). "Guidelines for implementing seismic base isolation in advanced nuclear reactors." Technical Report MCEER-23-0003, University at Buffalo, The State University of New York, Buffalo, NY.

Zhang, Z., Dong, Y., Li, F., Zhang, Z., Wang, H., Huang, X., Li, H., Liu, B., Wu, X., Wang, H., Diao, X., Zhang, H., and Wang, J. (2016). "The Shandong Shidao Bay 200 MWe high-temperature gas-cooled reactor pebble-bed module (HTR-PM) demonstration power plant: An engineering and technological innovation." *Engineering*, 2(1), 112-118.