Horizontal Split Table Conceptual Design for Advanced Reactor Validation

Mathieu N. Dupont[1], Justin B. Clarity[1], Daniel J. Siefman[2], and Catherine M. Percher[2]

[1]Oak Ridge National Laboratory
1 Bethel Valley Rd, Oak Ridge, TN 37830 USA

[2]Lawrence Livermore National Laboratory
7000 East Avenue, Livermore, CA 94550 USA

dupontmn@ornl.gov, clarityjb@ornl.gov, siefman1@llnl.gov, percher1@llnl.gov

ABSTRACT

Oak Ridge National Laboratory and Lawrence Livermore National Laboratory are collaborating to develop a conceptual design for a horizontal split table for use in performing critical experiments. The goal of this design effort is to provide nuclear data testing and validation capabilities for advanced reactors such as pebble-bed high-temperature gas-cooled reactors, molten salt reactors, and heat pipe microreactor, but it could also be used for the current generation of reactors. The first concept being explored for the horizontal split table, a pebble-bed design based on the HTR-10 reactor, is described in this paper. A critical configuration corresponding to a footprint of about 4.5 m^2 was determined with SCALE/KENO-VI to fit the planned dimensions of the horizontal split table. The similarity of the pebble-bed design and the HTR-10 reactor application was assessed using SCALE/TSUNAMI, and a similarity coefficient c_k of 0.9982 was obtained, proving that the concept will be useful for nuclear data validation and assimilation of pebble-bed type advanced reactors. In the proposed design, the materials with the highest k_{eff} sensitivity are graphite and uranium, demonstrating that particular care must be given to carbon-related cross-section data. The effect of mechanical uncertainties between the fixed and moving tables was also assessed by calculating the reactivity change caused by vertical and horizontal gaps, as well as angular and torsion offsets between the two sides of the horizontal split table concept. The highest relative changes on the concept's reactivity were caused by angular perturbations. The same analysis process is currently being used to create a molten salt advanced reactor type horizontal split table concept based on the Molten Salt Reactor Experiment (MSRE).

KEYWORDS: Critical experiment design, Graphite, Pebble-bed, Nuclear data

1. INTRODUCTION

Oak Ridge National Laboratory (ORNL) is exploring the value of using a horizontal split table (HST) concept to provide a nuclear data testing capability for advanced reactor designs. Many advanced reactor designs being considered would operate using materials that have not commonly been used in the current fleet of reactors, and they may operate in different neutron energy spectra and temperature ranges. These proposed reactor designs are using nuclear data that have not previously been considered in commercial reactor design: this may lead to poor reactivity predictions for these new designs. The adequacy of the nuclear data for a given application is determined by benchmarking with critical experiments that use similar nuclear data. Developing critical experiments with similar characteristics to advanced reactors may be challenging with the experimental assets currently available, such as vertical lift machines, because they have limited masses and volumes of assemblies that can be accommodated. The HST concept will provide the capability to perform critical experiments with larger volumes than the current experimental apparatuses and therefore may provide validation for these reactor designs.

The overall design of the HST concept is being led by Lawrence Livermore National Laboratory (LLNL). The LLNL staff have a preliminary HST design concept, shown in Fig. 1. The planned dimensions of the split table are between 91.44 to 182.88 cm half-table width and 91.44 to 121.92 cm half-table length. Thus, the planned dimensions of the table when assembled are 91.44 × 182.88 cm minimum, with 1.67 m^2 surface area, and 182.88 × 243.84 cm maximum, with 4.46 m^2 surface area. To simplify the study, ORNL decided to perform the conceptual design calculations while considering the maximum planned dimensions, as summarized in Table I. The dimensions shown in the concept in Fig.1 do not correspond to the maximum allowed dimensions.

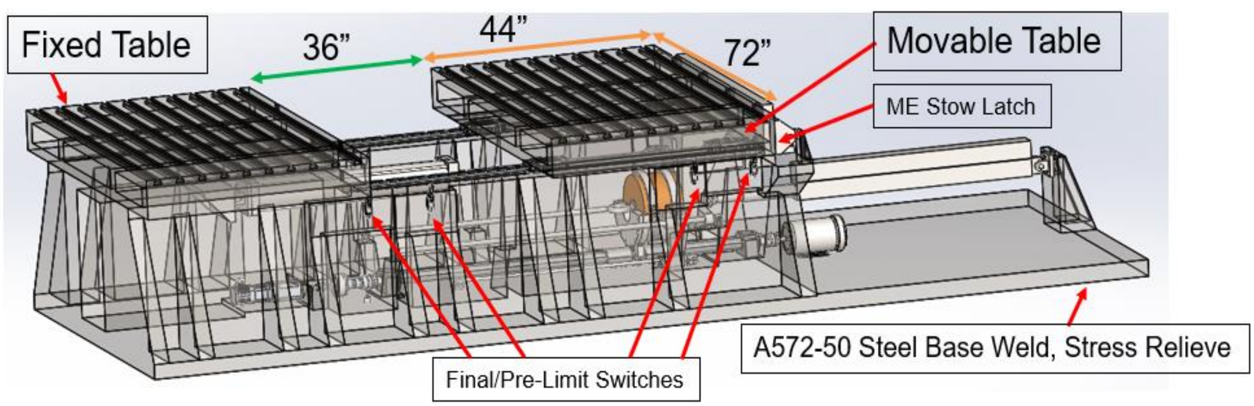

Figure 1. Example Rendering of the HST Concept Proposed by LLNL, dimensions in inches

Table I. Proposed maximum split-table dimensions by LLNL

Split table element	Width (cm)	Length (cm)	Surface area (m^2)
Fixed table	182.88	121.92	2.23
Moving table	182.88	121.92	2.23
Total	182.88	243.84	4.46

From this proposed HST device, design calculations of a critical experiment to validate a high-temperature, pebble bed reactor were performed. These sought to maximize the similarity between an experiment on the HST and an advanced reactor design. If a high similarity was found, this would help support the need and usefulness of a new HST critical experiment device. The design calculations are performed with different SCALE [1] modules: KENO-VI for the criticality calculation, TSUNAMI for the sensitivity determination, and TSUNAMI-IP for the concept/application similarity study, using the ENDF/B-VII.1 cross-section library. The selection of advanced reactor concepts to perform the similarity study are based on a technical memo written by F. Bostelmann et al. [2].

The remainder of the paper is organized as follows: Section 2 describes the methods used to determine the critical dimensions of HST experimental concepts and to analyze their similarity to the intended applications. Section 3 provides the results of the first study for a pebble-bed reactor concept based on the HTR-10 reactor. Section 4 briefly describes the second advanced reactor type to be studied: a molten salt reactor concept based on the MSRE. Section 5 provides the conclusions of this paper.

2. METHODS

2.1. Determination of Critical Core Experimental Configuration

For each HST advanced reactor type concept studied, a similar process is followed to determine a critical core:

1. A literature search is conducted to find a peer-reviewed, published, and publicly available reactor benchmark model corresponding to the advanced reactor type selected.
2. The model is converted to a SCALE/KENO-VI format if needed.
3. A simplified model of the reactor is created, keeping only the active core region.
4. The model is transformed to a cubic shape, and the dimensions are adjusted to be smaller than the HST planned maximum dimensions of 182.88 × 243.84 cm.
5. Incremental calculations are performed to determine a critical core corresponding to the HST planned dimensions, adjusting the reflector thickness on the sides, top, and bottom of the active core region. The calculations are performed with SCALE KENO-VI using the ENDF/B-VII.1 cross-section library.
6. The model is separated in half, corresponding to the two sides of the horizontal split table.

2.2. Evaluation of Nuclear Data Tested by the Experimental Configuration

After obtaining a critical core configuration, the TSUNAMI module of SCALE was used to calculate the k_{eff} uncertainty resulting from the use of ENDF/B-VII.1 cross-section library and to find the sensitivity of k_{eff} to the different materials in the core. The TSUNAMI output file allowed for further investigation of the cause of the k_{eff} material sensitivity, and it was possible to determine which nuclear isotope, nuclear reaction and/or mixture had the greatest influence on k_{eff}. TSUNAMI also creates a k_{eff} sensitivity file (.sdf file), allowing for plotting of any calculated sensitivity. If a sensitivity file was available from the whole core application literature search, then TSUNAMI-IP was used to calculate the correlation coefficient c_k between the whole core application and the newly designed HST core sensitivity files. A highly correlated c_k coefficient is proof that the HST concept design would be useful for nuclear data validation of the corresponding advanced reactor materials. As an additional test of nuclear data uncertainty influence on the critical core configuration, other cross-section libraries are used in calculations, such as ENDF/B-VII.0 or ENDF/B-VIII.0.

2.3. Assessment of Horizontal Split Table Mechanical Tolerances

Quantifying experimental uncertainties is an essential part of designing a critical experiment. Of particular interest in this study is understanding the level of reactivity change that would be induced by mechanical uncertainties on the HST concept for each advanced reactor concept. If these uncertainties are sufficiently small, the critical experiment will be of benchmark quality and therefore of high utility for validation. The four types of tolerances are a horizontal gap, a vertical gap, an angular gap, and a torsion offset, as shown in Fig. 2, similarly to a previous horizontal split-table design study [4]. A series of calculations varying each of these parameters is performed, and a quadradic equation is fit to those points. Based on the quadradic fit, the mechanical tolerance that would produce an acceptable experimental uncertainty can be determined. As a last step of the assessment, the two most significant tolerances contributions on k_{eff} of the four tested are further analyzed. The goal is to determine if the association of simultaneous tolerances perturbations on the same split table model has a greater influence on k_{eff} than the added separate effects.

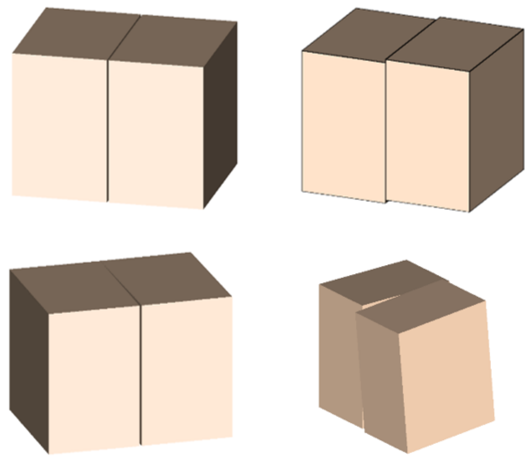

Figure 2. Depictions of the mechanical tolerances considered for each of the HST concepts: horizontal gap (upper left), vertical gap (upper right), angular gap (lower left), and torsional offset (lower right), similar to [3]

3. EXAMPLE HORIZONTAL SPLIT TABLE CONCEPT OF PEBBLE-BED HIGH-TEMPERATURE GAS-COOLED REACTOR

3.1. HTR-10 Application Case

As a first advanced reactor type studied, a pebble-bed high-temperature gas-cooled reactor was selected. The application chosen is the HTR-10 reactor, which is thoroughly described by Terry et al. [4] and previously modeled in SCALE/KENO-VI [5]. The active core region of this reactor measures 123 cm high and 180 cm in diameter. The core uses a combination of fuel pebbles and dummy graphite pebbles separated by air at 15°C. In total, approximately 16,890 pebbles are in the HTR-10: 9,627 fuel pebbles and 7,263 dummy pebbles, with a packing fraction of 61%. Each fuel pebble has a radius of 3.0 cm radius, with a fuel radius of 2.5 cm and 0.5 cm graphite shell. Each pebble's inner fuel region contains 8,355 TRISO fuel particles. Each TRISO fuel particle is a combination of an inner 17 wt.% UO_2 enriched fuel kernel with a radius of 0.025 cm and different coating layers of buffer, PyC, SiC, and PyC, with thicknesses of 0.009, 0.004, 0.0035, and 0.004 cm, respectively. The UO_2 density is 10.4 g/cm^3, and the graphite matrix and fuel pebble's outer shell density is 1.73 g/cm^3. Views of the HTR-10 core KENO-VI model are shown in Fig. 3 [5]. The left portion of Fig. 3 shows an isometric view with the front right portion of the model cut away. The upper right portion of the figure shows a detailed cutaway of the pebbles with the fuel region shown in purple and the graphite shown in beige. The bottom right portion shows a layer of pebbles in the active region of the core.

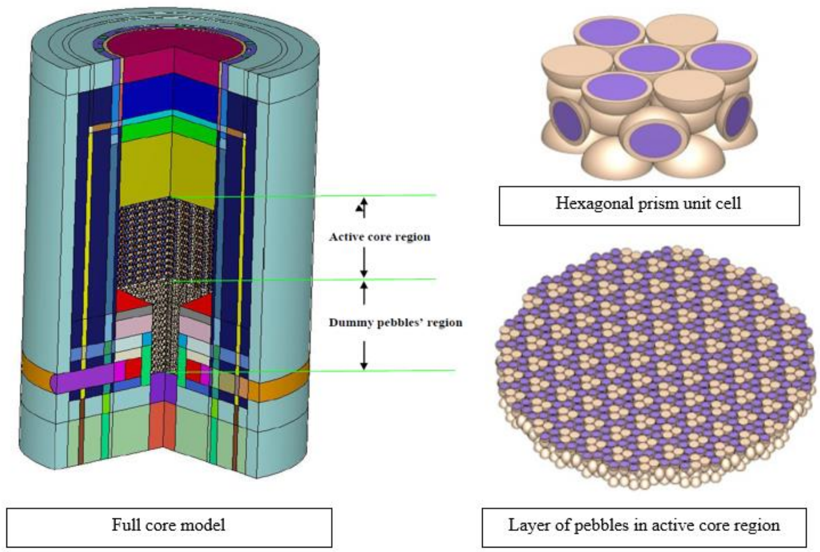

Figure 3. Depictions of the HTR-10 full core model (left), the prismatic unit cell (upper right), and a layer of the pebbles in the active region (lower right), illustrations from [5]

3.2. Horizontal Split Table Concept Critical Core Configuration

A KENO-VI whole core model of the HTR-10 [5] was used to create a horizontal split table concept model corresponding to the maximum dimensions described above: 182.88 × 243.84 cm. To create the HST concept, the procedure presented in Section 2.1 was closely followed. First, the HTR-10 model was modified to only keep the active core region, corresponding to the fuel and dummy pebbles association. Then, the model was transformed into a cubic shape, and a graphite reflector layer was added on the sides, top, and bottom to obtain a critical configuration at ambient temperature and pressure. Finally, the core was split in half to correspond to the two parts of the horizontal split table. Because this is the conceptual design phase, the manner in which the pebbles are cut at the split location was not considered. The modeled critical core active fuel region is 120 × 140 × 123.57 cm. Including the graphite layer, the core is 182 × 240 × 242.57 cm, slightly less than the LLNL dimension requirements. The critical HST pebble-bed concept KENO model is shown in Fig. 4. Using this configuration, a k_{eff} of 1.00019 ± 0.00020 was obtained with KENO-VI and the ENDF/B-VII.1 cross-section library.

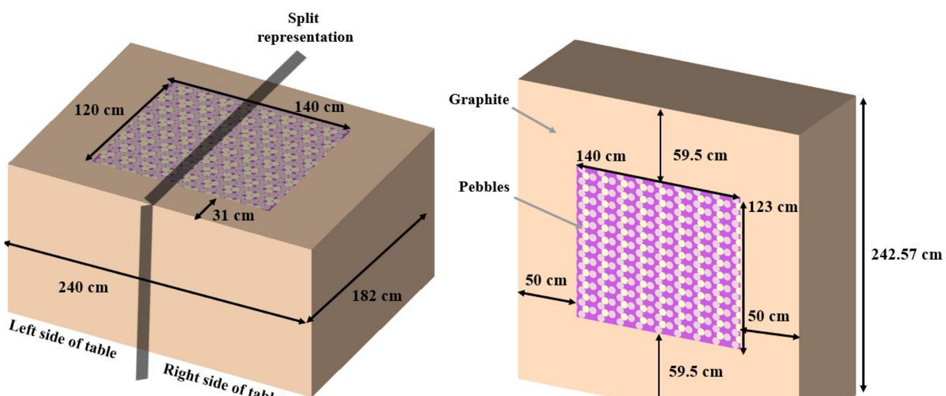

Figure 4. Dimensioned center-cut plane top view (left) and side view (right) of the pebble-bed reactor experimental concept

3.3. Horizontal Split Table Concept Nuclear Data Evaluation

3.3.1. Similarity analysis

SCALE/TSUNAMI was used to calculate the sensitivities of the critical horizontal split table to the materials cross-sections, and the results are shown in Table II. The results were confirmed by direct perturbations calculations. The sensitivity plots corresponding to the two highest contributors are shown in Fig. 5 for ^{235}U and Fig. 6 for graphite. In each figure, the sensitivity profiles of the original HTR-10 whole core and the newly design horizontal split table concept application are shown. The sensitivity profiles are very similar for ^{235}U. For graphite, the largest sensitivity peaks and the total sensitivity value are similar, but the HST application is overall smoother. This is likely the result of uncertainties in the HTR-10 TSUNAMI calculation. TSUNAMI-IP with the 56groupcov7.1 covariance matrix file was used to calculate the correlation coefficient c_k between the designed critical horizontal split table and the reference HTR-10 full-core reactor model, both for the cold zero power condition. The first step for any reactor design is cold critical to validate room temperature cross sections, so looking at ambient temperature is useful even if the reactor will operate at high temperature. The correlation coefficient obtained is c_k = 0.9982 ± 0.0045. The maximum value c_k can attain is 1, meaning the obtained correlation between the two models is very high: therefore, the use of a critical horizontal split table as designed could support cross-section validation of a pebble-bed advanced reactor similar to the HTR-10. The highest c_k value obtained from the available International Criticality Safety Benchmark Evaluation Project (ICSBEP) benchmarks [6] are 0.7164 and 0.7080 from IEU-SOL-THERM-001-003 and LEU-SOL-THERM-006-005, respectively.

Table II. HST design highest sensitivity contributors' results obtained with SCALE/TSUNAMI

Nuclide	Corresponding physical element in the model	TSUNAMI Results	
		Total Reaction Sensitivity $\left(\frac{\Delta k}{k} / \frac{\Delta\sigma}{\sigma}\right)$	Relative uncertainty (%)
^{235}U	Fuel kernel - UO_2	0.2503	0.02%
^{238}U	Fuel kernel - UO_2	-0.0378	0.12%
C-graphite	Graphite matrix in pebble	0.4229	2.89%
C-graphite	Pebble shell	0.0760	3.35%
C-graphite	Dummy pebble	0.1521	3.59%

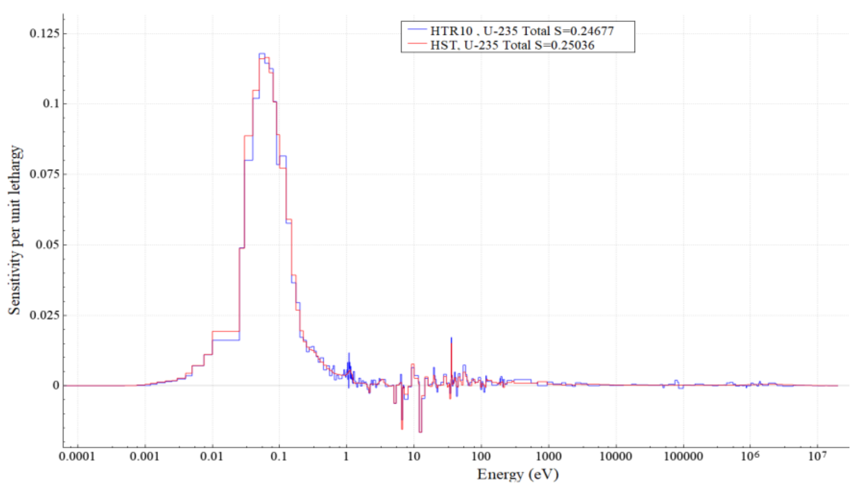

Figure 5. U^{235} total cross section sensitivity profiles for the HTR10 whole core and the horizontal split table concept.

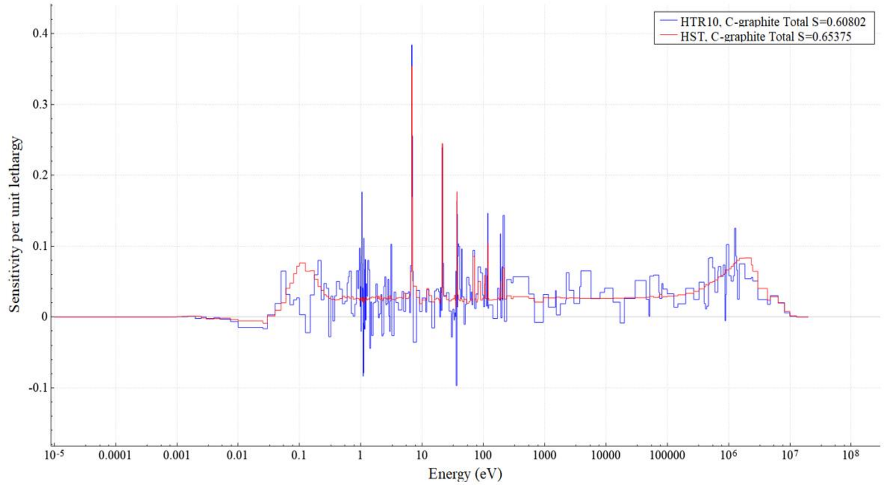

Figure 6. Graphite total cross-section sensitivity profiles for the HTR10 whole core and the horizontal split table concept.

3.3.2. Sensitivity to available nuclear data libraries

Apart from the ENDF/B-VII.1 cross-section library, calculations have been performed with the ENDF/B-VII.0 cross-section library. For the same base model, large k_{eff} discrepancies (about 1,000 pcm) were observed by using different cross-section libraries, as shown in Table III. Using the ENDF/B-VII.0 cross-section library for a model in a critical configuration with the ENDF/B-VII.1 cross-section library increased k_{eff} by about 1262 pcm. Oppositely, using the ENDF/B-VII.1 cross-section library for a model in a critical configuration with the ENDF/B-VII.0 cross-section library decreased k_{eff} by about 993 pcm. The discrepancies are mostly due to the carbon capture cross-section update between the two versions of the library. The discrepancies between ENDF/B-VII.0 and ENDF/B-VII.1 have been observed in previous studies [2]. This observation shows that the nuclear data currently used are still not perfect, and the designed concept would be very useful to help improving it.

Table III. k_{eff} discrepancies from different cross-section libraries

Model	Critical core with ENDF/B-VII.1	Critical core with ENDF/B-VII.1	Critical core with ENDF/B-VII.0	Critical core with ENDF/B-VII.0
Cross-section library	ENDF/B-VII.1	ENDF/B-VII.0	ENDF/B-VII.0	ENDF/B-VII.1
Table size	240×182×242.574	240×182×242.574	240×182×220	240×182×220
k_{eff}	0.99963	1.01225	1.00075	0.99082
Delta k_{eff} from critical configuration (pcm)	0	+1262	0	-993

3.4. Horizontal Split Table Concept Assessment of Mechanical Tolerances

A study was performed of the experimental uncertainties in k_{eff} associated with the mechanical tolerances discussed in Section 2.3. The results of the sensitivity calculations for each of the mechanical tolerances are presented in Fig.7, along with quadradic fits to the data. The fits were used to determine the mechanical tolerances that would result in experimental uncertainties ranging from 0.00010 to 0.00200 Δk_{eff}, as shown in Table IV.

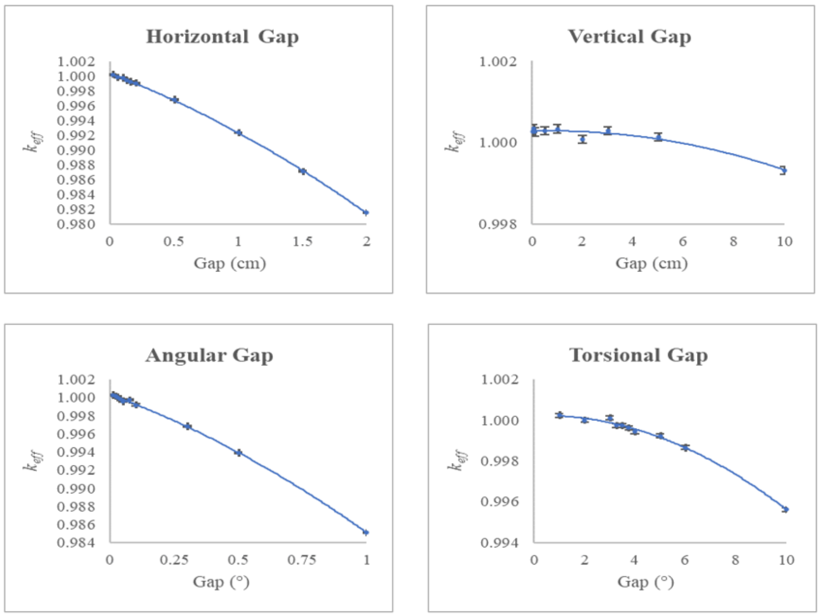

Figure 7. Dimensional sensitivity calculations for the horizontal (upper left), vertical (upper right), angular (lower left), and torsional (lower right) gap cases.

Table IV. Interpolated geometric uncertainties necessary to yield experimental uncertainties for the PBMR experimental concept

Interpolated Δk_{eff}	Horizontal gap (cm)	Vertical gap (cm)	Angular gap (°)	Torsional offset (°)
-0.00010	0.040	5.00	0.0235	2.10
-0.00020	0.055	6.00	0.033	2.60
-0.00050	0.099	8.10	0.061	3.68
-0.00100	0.170	10.70	0.106	4.95
-0.00200	0.308	14.45	0.191	6.78

Of the four configurations tested, the two most significant mechanical tolerance contributions to k_{eff} were from horizontal and angular gaps. A comparison of the simultaneous perturbations on the same split table model and the added separate-effects influence on the nominal k_{eff} is shown in Fig. 8, with a description of the cases studied given in Table V. The combined effects had a similar influence on k_{eff} compared to the addition of the separate effects below 0.5 cm horizontal and 0.1-degree gaps. On larger gaps, the combined effects had a greater influence on k_{eff} compared to the addition of the separate effects, with approximately 600 pcm difference for 2 cm horizontal and 1-degree angular gaps, for example.

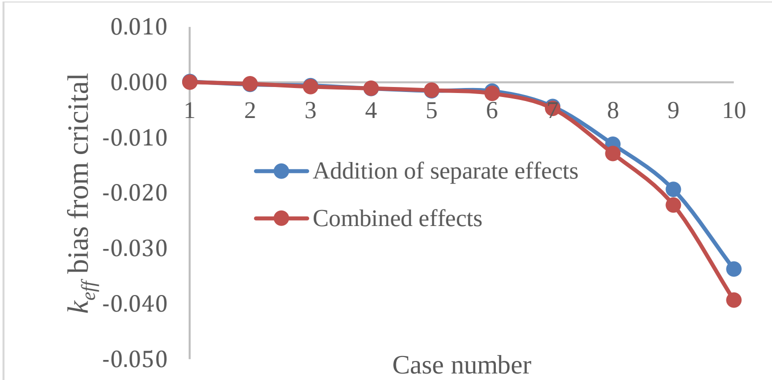

Figure 8. Comparison of the k_{eff} bias from critical of the simultaneous horizontal and angular gap perturbations to the added separate effects.

Table V. Description of the different cases corresponding to the simultaneous horizontal and angular gap perturbations

Case number	Horizontal gap (cm)	Angle gap (degrees)	Case number	Horizontal gap (cm)	Angle gap (degrees)
1	0.02	0.01	6	0.2	0.075
2	0.06	0.02	7	0.5	0.1
3	0.1	0.03	8	1	0.3
4	0.13	0.04	9	1.5	0.5
5	0.16	0.05	10	2	1

4. FUTURE WORK

The next advanced reactor HST conceptual design being studied is a molten salt reactor based on the Molten Salt Reactor Experiment (MSRE). The MSRE was built at ORNL and operated between 1965 and 1969. It is one of the few molten salt reactors that has been built with available experimental data. The study is based on a SCALE model of the MSRE that was developed in 2021 [7]. The same process described in section 2 is applied to create a molten salt reactor critical conceptual design to be used on the horizontal split table. A front-right quarter of the MSRE model and the corresponding preliminary horizontal split table design are shown in Fig. 9.

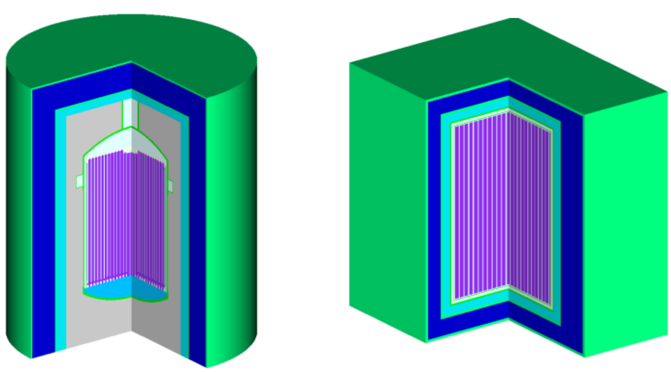

Figure 9. Front-right quarter section of the MSRE SCALE model used as a basis for the HST molten salt reactor conceptual design (left) [7], horizontal split table preliminary design (right).

5. CONCLUSIONS

A methodology was developed to create conceptual designs of benchmark critical experiments for advanced reactor nuclear data testing and validation using a horizontal split table (HST) concept. The first type of advanced reactor that was explored was the pebble-bed high-temperature gas-cooled reactor, based on the previously characterized HTR-10 reactor. Design calculations were performed using different modules of SCALE and the ENDF/B-VII.1 cross-section library. A critical configuration was determined matching the required machine dimensions, thus proving the conceptual feasibility of the design. The very high correlation between the HST design and the HTR-10 application case proves that the developed design is similar to the application. Performing such critical experiments would support the nuclear data testing, validation, and assimilation [8] necessary for any project to build similar reactors. After observing the significant influence of graphite on the criticality of the experiment, it was concluded that carbon cross-section data must be thoroughly examined. The second type of advanced reactor being studied is a molten salt reactor, with the MSRE as a basis. A process similar to that used for the pebble-bed type concept is being followed, with a goal of determining the feasibility of a horizontal split table design corresponding to this advanced reactor type for which nuclear data are to be focused. Other advanced reactors types such as heat-pipe reactors may also be explored.

ACKNOWLEDGMENTS

This work was supported by the by the Nuclear Criticality Safety Program, funded and managed by the National Nuclear Security Administration for the US Department of Energy.

REFERENCES

1. W. A. Wieselquist, R. A. Lefebvre, and M. A. Jessee, Eds., *SCALE Code System*, Oak Ridge National Laboratory, Oak Ridge, TN, ORNL/TM-2005/39, Version 6.2.4 (2020).
2. F. Bostelmann, G. Ilas, and W. A. Wieselquist, *Key Nuclear Data Impacting Reactivity in Advanced Reactors*, Oak Ridge National Laboratory, Oak Ridge, TN, ORNL/TM-2020/1557 (2020).
3. A. D. Miller and G. Harms, *Integral Experiment Request 226 CED-1 Summary Report Horizontal Split-Table Critical Assembly Conceptual Design for Sandia Experiments*, Sandia National Laboratories, Albuquerque, NM, SAND2013-10178P (2013).
4. W. K. Terry et al., "Evaluation of the Initial Critical Configuration of the HTR-10 Pebble-Bed Reactor," (HTR10-GCR-RESR-001), *International Handbook of Evaluated Criticality Safety Benchmark Experiments*, Organisation for Economic Co-operation and Development, Nuclear Energy Agency, Paris, France, NEA/NSC/DOC(2006)1, Rev. 0, (2007).
5. G. Ilas et al., *Validation of SCALE for High Temperature Gas-Cooled Reactor Analysis*, NUREG/CR-7107 (ORNL/TM-2011/161), US NRC (2012).
6. *International Handbook of Evaluated Criticality Safety Benchmark Experiments*, Organisation for Economic Co-operation and Development, Nuclear Energy Agency, Paris, France, NEA:7328, (2019).
7. F. Bostelmann, S. Skutnik, E. Walker, G. Ilas, and W. A. Wieselquist, "Modeling of the Molten Salt Experiment with SCALE," Journal Article in Press (2021).
8. G. Palmiotti, P. Blaise, F. Mellier, "M. Salvatores: integral experiments and their use for the validation of nuclear data and the neutronic design of advanced nuclear systems," *EPJ Nuclear Sci. Technol.* **7** (11) (2021).