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# PRELIMINARY BENCHMARK EVALUATION OF JAPAN'S HIGH TEMPERATURE ENGINEERING TEST REACTOR

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## ABSTRACT

A benchmark model of the initial fully-loaded start-up core critical of Japan's High Temperature Engineering Test Reactor (HTTR) was developed to provide data in support of ongoing validation efforts of the Very High Temperature Reactor Program using publicly available resources. The HTTR is a 30 MWt test reactor utilizing graphite moderation, helium coolant, and prismatic TRISO fuel. The benchmark was modeled using MCNP5 with various neutron cross-section libraries. An uncertainty evaluation was performed by perturbing the benchmark model and comparing the resultant eigenvalues. The calculated eigenvalues are approximately 2-3% greater than expected with an uncertainty of ±0.70%. The primary sources of uncertainty are the impurities in the core and reflector graphite. The release of additional HTTR data could effectively reduce the benchmark model uncertainties and bias. Sensitivity of the results to the graphite impurity content might imply that further evaluation of the graphite content could significantly improve calculated results. Proper characterization of graphite for future Next Generation Nuclear Power reactor designs will improve computational modeling capabilities. Current benchmarking activities include evaluation of the annular HTTR cores and assessment of the remaining start-up core physics experiments, including reactivity effects, reactivity coefficient, and reaction-rate distribution measurements. Long term benchmarking goals might include analyses of the hot zero-power critical, rise-to-power tests, and other irradiation, safety, and technical evaluations performed with the HTTR.

*Key Words*: HTTR, TRISO, graphite, IRPhEP, benchmark

## 1. INTRODUCTION

One of the high priority benchmarking activities for corroborating the Next Generation Nuclear Plant (NGNP) Project and Very High Temperature Reactor (VHTR) Program is evaluation of Japan's existing High Temperature Engineering Test Reactor (HTTR). The HTTR (Fig. 1) is a 30 MWt engineering test reactor utilizing graphite moderation, helium coolant, and prismatic TRISO fuel. A large amount of critical reactor physics data is available for validation efforts of High Temperature Gas-cooled Reactors (HTGRs).

Previous international reactor physics benchmarking activities provided a collation of mixed results that inaccurately predicted actual experimental performance. [1] Further reevaluations were performed by the Japanese to reduce the discrepancy between actual and computationally-determined critical configurations. [2-3] Current efforts at the Idaho National Laboratory (INL) involve development of reactor physics benchmark models in conjunction with the International Reactor Physics Experiment Evaluation Project (IRPhEP) [4] for use with verification and

validation methods in the VHTR Program. The initial fully-loaded, cold-critical, configuration of the HTTR start-up core [5] was evaluated for inclusion in the IRPhEP Handbook in preparation for further evaluation of HTTR experimental physics data. [6]
The active HTTR core has a height of 290 cm, an effective diameter of 230 cm, and contains a total of 30 fuel columns. Each column contains five hexagonal graphite fuel blocks that are 580 mm high and 360 mm across flats. Control rod guide blocks, replaceable reflector blocks, and irradiation blocks have the same dimensions, and all blocks are stacked vertically within the core. Fuel compacts containing TRISO particles with LEU-$O_2$ (~6 wt.% average enrichment across the entire core) kernels are placed in graphite sleeves and inserted into coolant channels within the fuel blocks. Sixteen pairs of control rods are used for reactivity control.

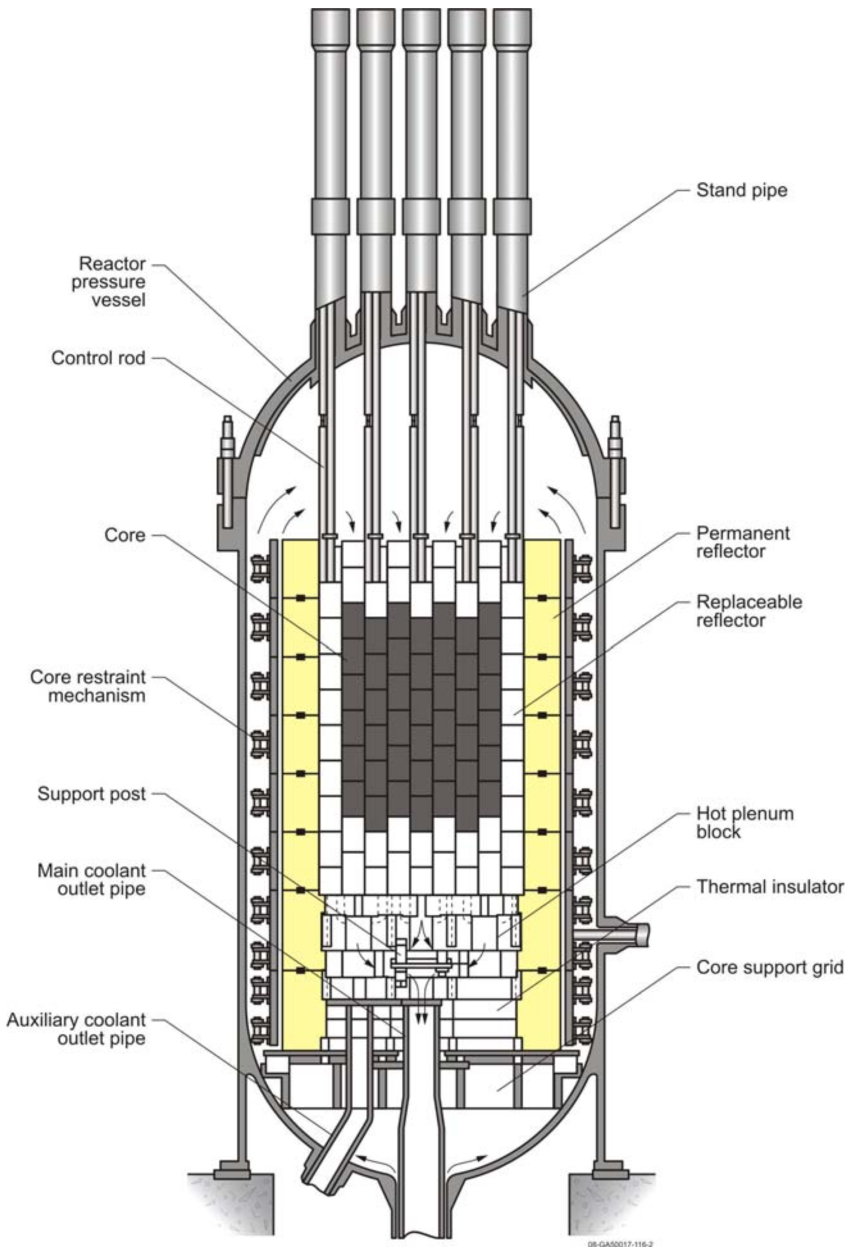


**Figure 1. Vertical Cross Section of the HTTR.**

Dummy blocks were replaced during the initial fuel loading of the core, starting from the core periphery towards the center (Fig. 2), such that various symmetric annular cores could be analyzed. Annular cores demonstrate inherent safety characteristics in the event of coolant loss and are of particular interest in developing high-temperature gas-cooled reactors (HTGRs). The initial start-up cores had 19, 21, 24, 27, and 30 fuel columns completely filled; a second configuration of the 24-column core was also performed by varying the control rod heights to achieve criticality. [5]

Publicly available reports and journal articles had been reviewed and collated for development of the benchmark evaluation. Unfortunately, sufficient information was unavailable for the generation of a highly detailed HTTR model.

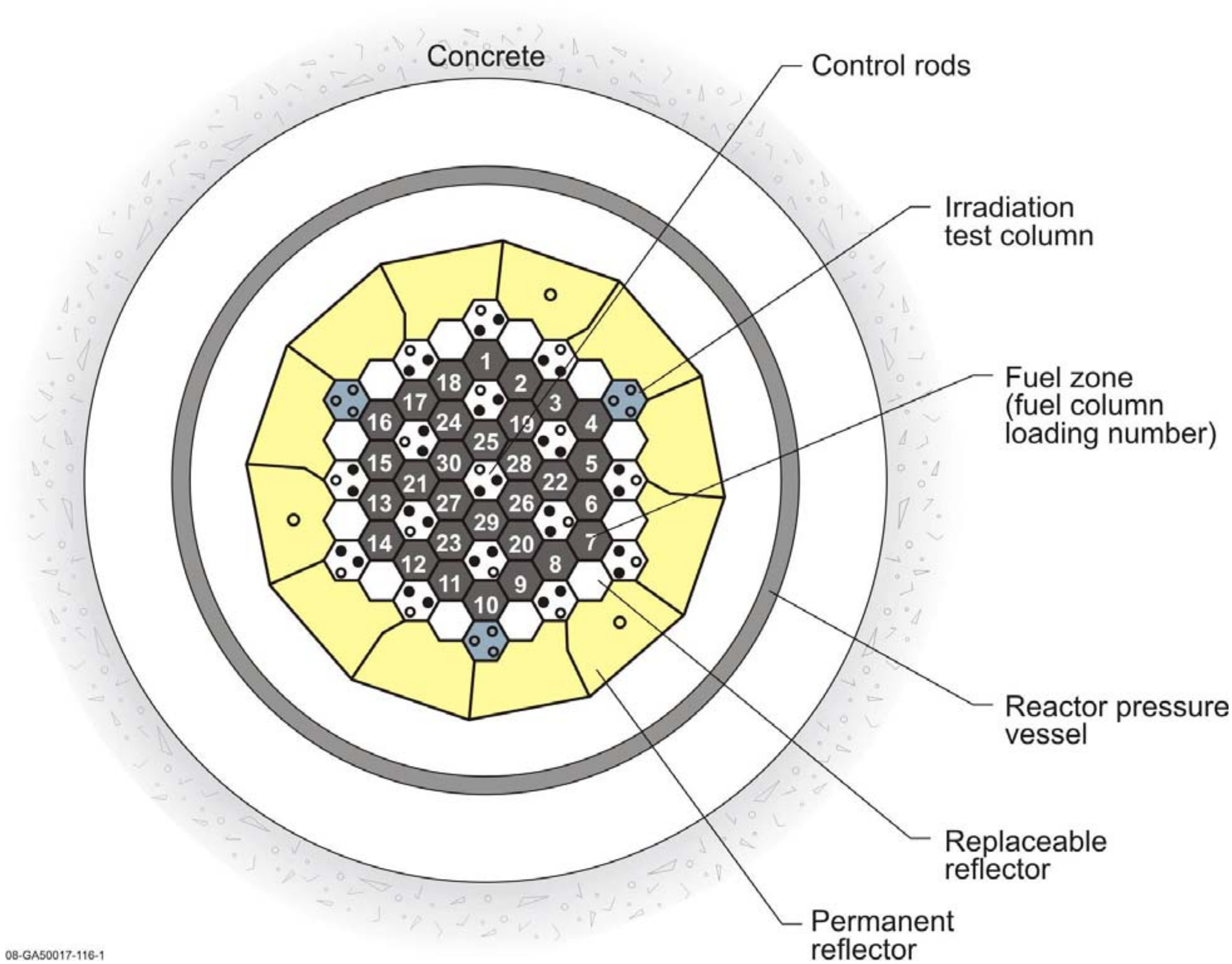


**Figure 2. Horizontal Cross Section of the HTTR.**

# 2. DESCRIPTION OF ACTUAL WORK

## 2.1. Examination of Available HTTR Data

Select resources were employed in the ascertainment of the dimensions, compositions, and uncertainties publicly available for defining and analyzing the HTTR benchmark. [1, 2-5, 7-8] Nozomu Fujimoto, from the Oarai Research Development Center, was instrumental in correctly identifying appropriate application of the uncertainties in the open literature. Unfortunately, much of the data regarding the HTTR that would be fundamental in developing an in-depth benchmark analysis are not published because this information applies to the current HTTR core configuration and fuel loading. The benchmark analysis of the HTTR data was performed using MCNP5. [9]

## 2.2. HTTR Benchmark Model Development

A comprehensive definition of the benchmark model may be found elsewhere. [6] In summary, the basic ingredient of the HTTR fuel is the TRISO particle consisting of a 600 μm $UO_2$ kernel surrounded by four coatings: a low density porous pyrolytic carbon (PyC) buffer layer, a high density inner isotropic PyC layer, a SiC layer, and a final outer PyC layer. These particles are coated in graphite and formed into annular fuel compacts containing ~13,000 TRISO particles apiece. A stack of 14 compacts forms a single fuel pin and is clad in a graphite fuel sleeve. A single hexagonal fuel block contains either 31 or 33 fuel pins depending on its location within the core. The HTTR active core contains a total of 150 fuel blocks. Because detailed dimensions of the fuel blocks are unavailable, features such as interconnecting dowels and sockets, fuel channel guides, and the fuel handling holes were not modeled, but the effective decrease in material density of the IG-110 graphite was approximated and accounted for in the model.

Each fuel block contains three holes, two of which contain burnable poison pellets which were used to counteract the large initial excess reactivity from the fresh fuel in the reactor. These were optimized to reduce deviation from the optimum power distribution due to burnup effects. [8] Although dummy blocks were utilized in the annular start-up cores, the fully-loaded HTTR core did not consist of any.

The HTTR utilizes 16 pairs of control rods: seven in the fueled region of the core and nine in the replaceable reflector region surrounding the core. Each control rod consists of ten segments of annular sintered $B_4C$/C compacts (natural boron concentration of 30 wt.%) contained within Alloy 800H cladding. Control rod guide blocks are stacked with holes for each control rod in a pair, as well as a hole for an emergency reserve shutdown system (RSS) consisting of loose $B_4C$/C pellets. While the RSS hole is retained in the model, no other components of the RSS are within the model boundaries. The HTTR also contains three columns of blocks with holes for instrumentation, identical to the control column blocks. Information regarding the dimensions and composition of the instrumentation, however, were not available.

The fueled region of the core is surrounded by a reflector region consisting of both replaceable and permanent reflector blocks. The replaceable blocks are stacked axially around the columns of fuel blocks. Additional reflector blocks are placed above and below the fuel blocks such that a column of five fuel blocks has two reflector blocks above it and another two below it. Finally a permanent reflector consisting of PGX graphite surrounds the entire core.

The entire benchmark model of the HTTR is represented by core of 522 cm in height and a diameter of 423 cm. A diagram representing the positioning of core components with the benchmark model is shown in Fig. 3. Control rods were withdrawn to achieve criticality; rod withdrawal heights are shown in Fig. 4.

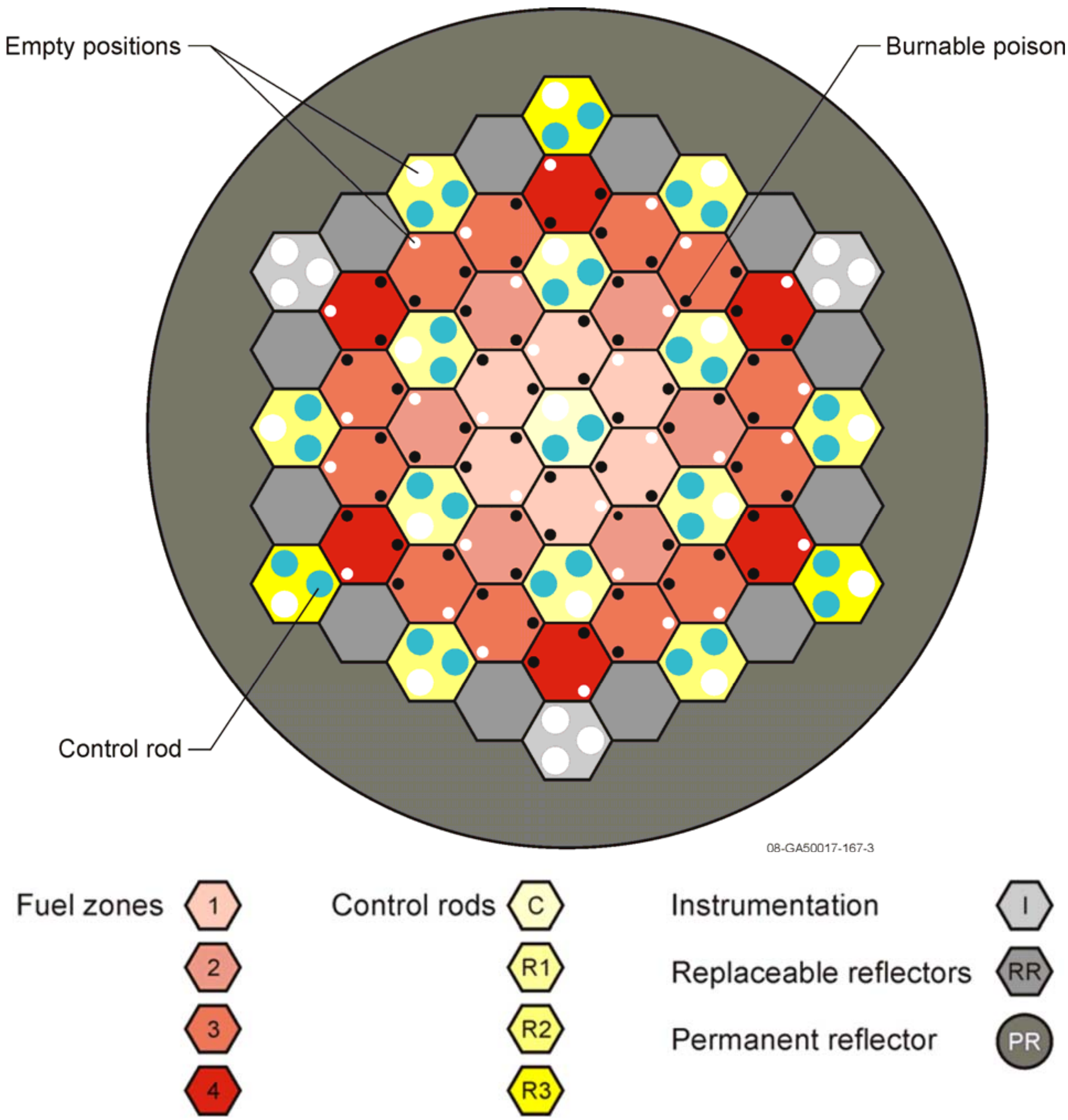


**Figure 3. HTTR Core Positions and Orientation.**

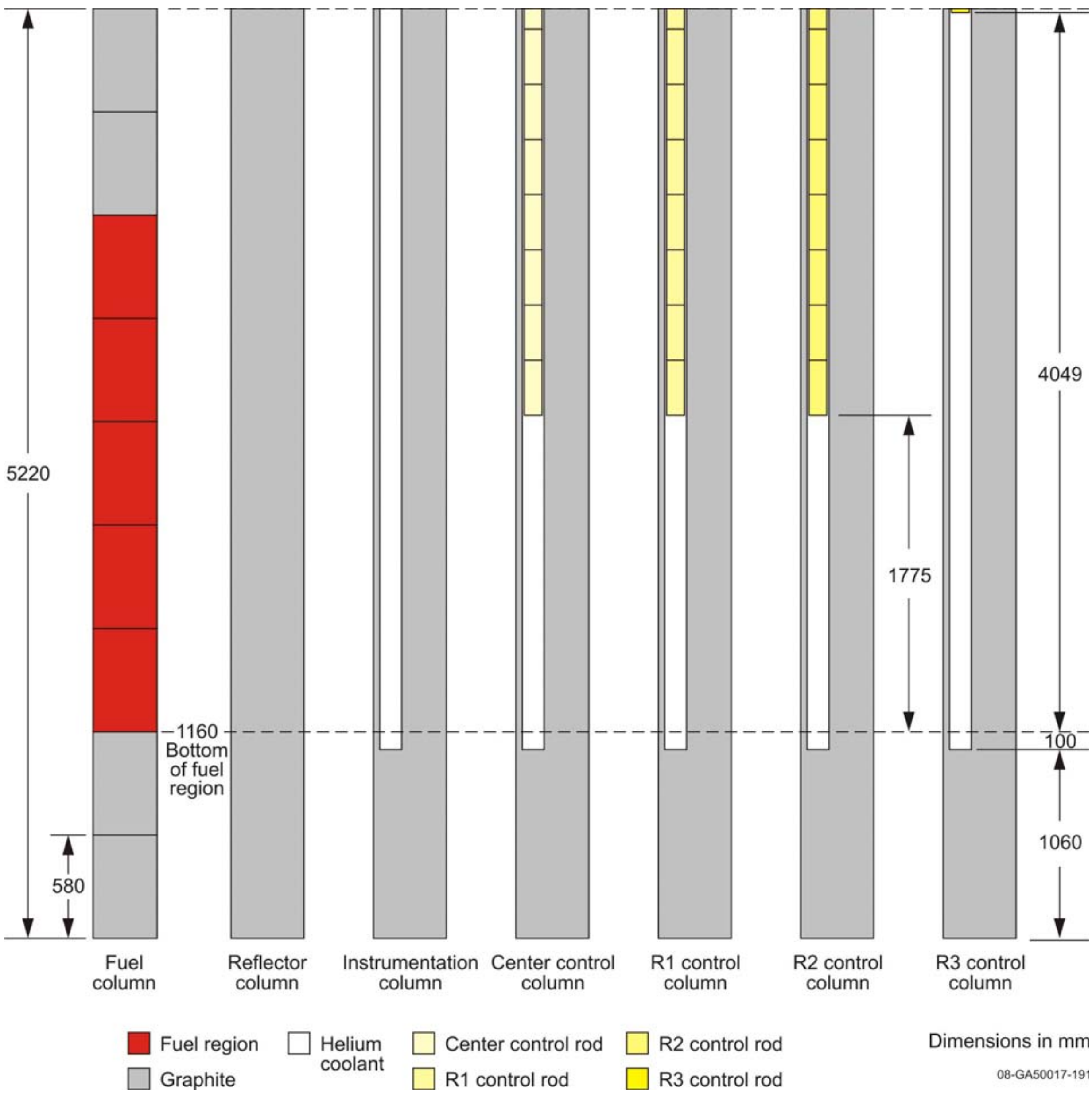


**Figure 4. Critical Rod Heights for the Fully-Loaded HTTR Core.**

Because the HTTR core consists of an optimized placement of fuel blocks containing 12 different enrichments of TRISO, explicit modeling of a core containing randomly placed particles is currently not feasible using MCNP5. Therefore two versions of the benchmark model were prepared to characterize the effect of TRISO particle placement within the fuel compacts while conserving mass. One model consisted of compacts modeled with a uniform fill of TRISO particles, truncating some of the particles along the edges of the compact. A second model was generated in which TRISO particles were modeled solely without truncation in an ordered lattice within the compact, having slightly less distance between particles than in the uniform fill model while still maintaining an overall packing fraction of 30%.

## 2.3. Analysis of the HTTR Benchmark

Due to limitations in the data, an effective bias between the physical HTTR experiment and the benchmark model could not be properly assessed. Analysis of possible room return effects and voiding of the helium coolant proved negligible. Eigenvalues, $k_{eff}$'s, for the HTTR benchmark were obtained using MCNP5 using different neutron cross-section libraries, such as ENDF/B-V.2, -VI.8, and -VII.0, JEFF-3.1, and JENDL-3.3, Uncertainties in the experimental configuration were assessed through perturbation of their respective parameters in the model to obtain a difference in the computed eigenvalues, $\Delta k$. The statistical uncertainty in the MCNP calculations was less than 0.00014, resulting is a $\Delta k$ uncertainty of approximately 0.00020, assuming no correlation between individually perturbed results. The main categories for uncertainty evaluation include experimental measurements, geometrical properties, compositional variations, and computational analyses.

Experimental measurements include data directly related to the configuration of the critical experiment such as temperature and control rod position. Geometric uncertainties include physical uncertainties in the fabrication tolerances of HTTR components such as diameter, thickness, and pitch. Composition variation includes uncertainties in fuel enrichment, material density, impurity content, boron absorber content, isotopic abundance of boron, and clad composition. Uncertainties in the computational analyses include investigation of room return effects, the stochastic modeling of TRISO particles, and the use of random number generation in the MCNP code.

Core parameters with known uncertainties were assessed using the perturbation method. Estimates were developed for parameters without reported uncertainties based on additional literature review (such as for potential impurities in clad material), comparison of variations in reported parameters across the multiple HTTR reports, and on variation of the least significant digit of the reported value within physical constraints (maximum and minimum dimensions of a fuel pin sleeve) or possible measurement limits (an enrichment of 9.9 wt.% would have an uncertainty of ±0.1 wt.%. Uncertainties were adjusted to obtain a $1\sigma$ uncertainty in $\Delta k$ for each parameter.

In all cases where tolerances or observed variations apply to large numbers of objects (TRISO particles, fuel pins, fuel blocks, etc.), both systematic uncertainties (applying to all the objects equally) and random uncertainties (different from one object to the next) will occur. In all cases, division by such large numbers of objects would make the random component of the uncertainty negligible. Positional dependence of objects within the assembly also influences the effective proportional effect on the resultant total uncertainty and bias calculations. However, since no information is available about how the uncertainties are divided between the systematic and random components, it is assumed throughout that the uncertainties are 25% systematic and 75% random. This assumption provides a basic prediction of the effect on $k_{eff}$ until additional information regarding systematic uncertainties of the HTTR can be obtained. The 25% systematic uncertainty is bound by the fact that most systematic uncertainties would be below 50% of the total uncertainty and above the historic approach of ignoring the unknown systematic components (i.e., treat it with a 0% probability). In actuality, careful experimenters may have an unknown systematic uncertainty that is approximately 10-15% of their total reported uncertainty.

Some uncertainties are treated as 100% systematic, as they do not contain a known random component; further release of information may affect this approach, however. The completely systematic parameters include temperature, fuel enrichment, impurities, and isotopic abundance of boron.

The total uncertainty in the benchmark is assessed by taking the root-mean-square of all the individual systematic and random uncertainties. The primary constituents of the total uncertainty are also identified.

## 3. RESULTS AND DISCUSSION

### 3.1. Benchmark Model Eigenvalues

The calculated eigenvalues, according to the neutron cross section library implemented, for the ordered and uniform fill models of the HTTR benchmark are shown in Table I. Because thermal scattering data for the JENDL-3.3 library was unavailable, the ENDF/B-VI.8 thermal scattering data was applied with the JENDL-3.3 eigenvalue analysis. The difference between the two models is less than 0.2%, which is similar to results gathered at the University of Michigan for the explicit modeling of fuel in a VHTR. They determined that the effect of modeling with a uniform lattice and clipped TRISO particles would reduce the calculated $k_{eff}$ value by approximately 0.1%. [10] The primary driver for this phenomenon might be explained by the Dancoff-Ginsberg factor, where in a lattice, the closer the lumps of fissionable material are to each other, the greater the shadowing effect and the smaller the resonance integral for the interacting lattice, which results in an increase in the non-leakage probability and a net increase in $k_{eff}$. [11]

**Table I. Computed Eigenvalues for the HTTR Benchmark.**

| Neutron Library | Ordered Fill | Uniform Fill | Difference |
|---|---|---|---|
| ENDF/B-V.2 | 1.0233 | 1.0231 | 0.02% |
| ENDF/B-VI.8 | 1.0253 | 1.0237 | 0.16% |
| ENDF/B-VII.0 | 1.0260 | 1.0242 | 0.18% |
| JEFF-3.1 | 1.0271 | 1.0252 | 0.18% |
| JENDL-3.3 | 1.0216 | 1.0200 | 0.16% |

The calculated eigenvalues for the benchmark models are approximately 2-3% greater than an expected experimental delayed-critical $k_{eff}$ value of 1.0000. Whereas biases regarding simplifications and approximations in the model could not be assessed due to limitations in information, the approximate difference between the models and a biased experimental eigenvalue might be less. Further acquisition of HTTR data would be necessary to accurately determine any biases and update the benchmark model.

Previous benchmarking activities by the international community over predicted criticality for the HTTR. [1] Further efforts by the Japanese reduced this modeling overestimate by accounting for modeling errors in air content in the graphite, simplification of graphite geometry, and impurity content in the graphite dummy blocks. [2-3] A similar analysis of potential air content in the graphite blocks was performed using MCNP; results were negligible and therefore inconclusive. However, the total quantity of air believed to be contained within the graphite was unreported.

Typically, significant contribution to negative reactivity in the graphite blocks is from impurities. A slight increase in the equivalent boron content of the core graphite can significantly decrease the effective eigenvalue: -0.013 ± 0.0003 $\Delta k_{eff}$/ppm and -0.0019 ± 0.0003 $\Delta k_{eff}$/ppm for impurities in the graphite blocks and permanent reflector, respectively. Comparison against other available benchmark experiments with graphite and uranium fuel demonstrate possible overestimation of the eigenvalue by 1-2% [12-13] except where the graphite composition is well characterized. [14] Benchmark evaluations demonstrated sensitivity to boron content in the graphite, which often comprised a significant portion of the total uncertainty. [13-15] It is quite possible that the equivalent boron content of the HTTR graphite may actually be greater than reported, resulting in a significant decrease in the calculated eigenvalues for the benchmark model.

### 3.2. Uncertainties in the Benchmark Model

A comprehensive enumeration of the entire uncertainty analysis variables and perturbations would be too lengthy to discuss here, and are retained elsewhere for public use. [6] The total uncertainty in the benchmark model, based on the assumption that all uncertainties with random components retain 25% as systematic, is within ±0.0070 $\Delta k_{eff}$ ($1\sigma$). The influence of the random components of uncertainty is relatively negligible (<0.0005 $\Delta k_{eff}$) compared to the overall uncertainty. Figure 5 shows the effect of assuming a ratio of systematic to random uncertainty for components that are not 100% systematic in nature.

The dominant factors in the total uncertainty of the benchmark model is the tolerance limits of impurities in the IG-110 graphite used in the core blocks and the PGX graphite blocks in the surrounding permanent reflector. These uncertainties are treated as 100% systematic as the individual impurity composition and distribution of the core graphite blocks is unspecified. It should be further noted that proper and thorough analysis and characterization of the graphite to be used in future NGNP reactors should be an absolute necessity as part of the selection process. [16-17] The capabilities to accurately model and predict reactor performance will be very sensitive to the composition of the primary constituent of the reactor core, the graphite.

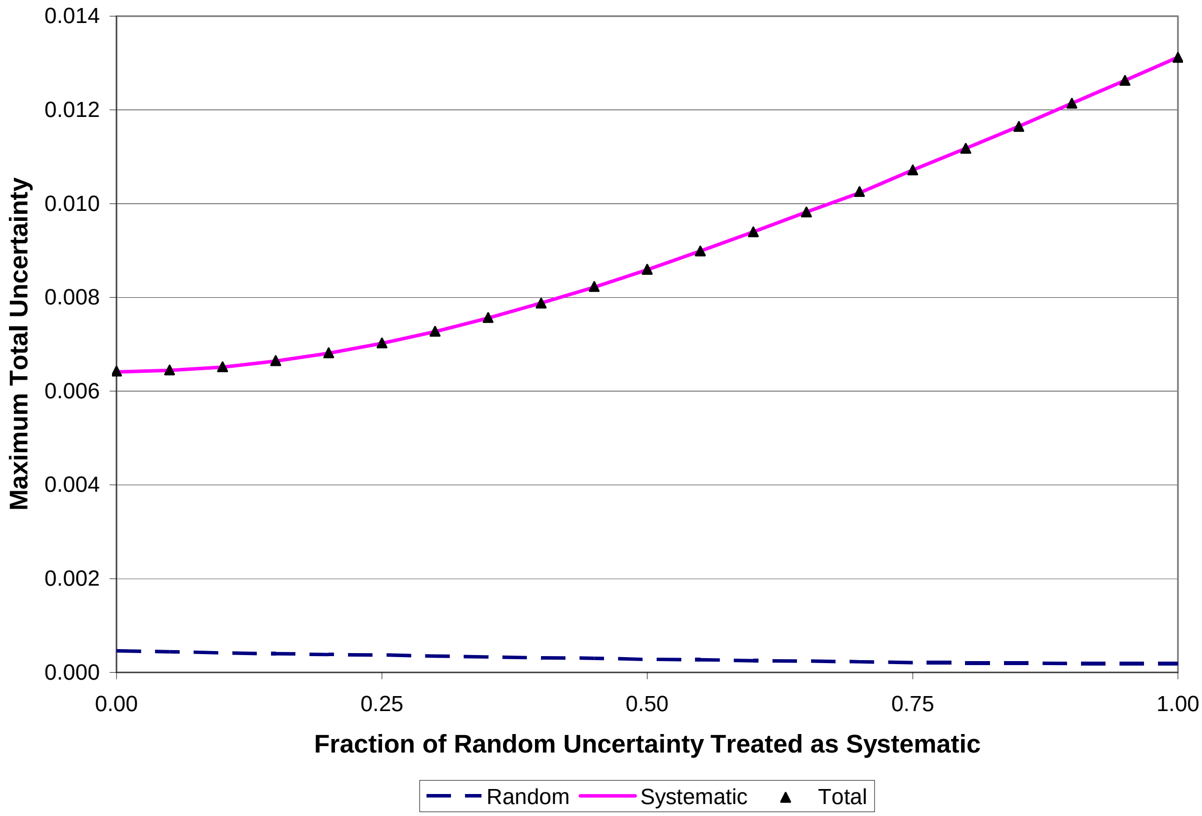


**Figure 5. Uncertainty Components of the HTTR Benchmark.**

### 3.3. Continuation of HTTR Benchmark Activities

Current benchmark values are on the order of 3σ to 4σ greater than the expected experimental value. The accrual of additional HTTR data is necessary to improve the quality of the benchmark analysis prior to assessment of the implication of the calculated benchmark results. The preservation of the benchmark as a report in the IRPhEP handbook will facilitate its update and public availability as additional information becomes available.

Current efforts at the INL include benchmark analysis of the five annular cores generated during the initial fuel loading of the start-up HTTR core. Annular cores demonstrate inherent safety characteristics and are of interest in developing future HTGRs.

Additional benchmarking activities in the near future include a comprehensive analysis of the remaining start-up core physics tests including reactivity effects measurements such as excess reactivity, shutdown margin, and control rod worth; reactivity coefficient measurements such as the isothermal temperature coefficient; and axial reaction-rate distribution measurements. Analysis of these additional reactor physics data could provide additional insight into potential problems or limitations of the HTTR benchmark model, and its potential for use in VHTR validation activities.

Long-term evaluation opportunities might include benchmarking of the hot zero-power critical; the rise-to-power tests; or other irradiation, safety, and technical experiments and evaluations performed using this high-temperature reactor core.

## 4. CONCLUSIONS

A benchmark model of Japan's HTTR was developed for the initial fully-loaded start-up core critical according to guidelines provided for inclusion in the IRPhEP Handbook, so as to provide data in support of ongoing validation efforts for VHTR Program activities. This preliminary reactor physics benchmarking effort provides the basic model for further examination of the remaining start-up core physics tests and of additional experimental data later generated at Japan's HTTR facility. The model was developed and analyzed using MCNP5 and perturbation techniques.

The current evaluation of the HTTR fully-loaded, start-up core critical experiment using publicly available information has an uncertainty of ±0.70% $\Delta k_{eff}$ (1σ) and an effective bias between the calculated and expected experimental eigenvalues of approximately 2-3%. Random uncertainties that can be reduced by the $\sqrt{N}$ due to the multiplicity of components (i.e., TRISO particles, fuel compacts, graphite blocks, etc.) are treated as 25% systematic and 75% random; the random uncertainty is quite negligible. Systematic treatment of the random uncertainty was implemented to preserve the unresolved details and assumptions used in the benchmark evaluation. The major constituents of the overall uncertainty are the impurities in the IG-110 graphite blocks used in the core and impurities in the PGX graphite blocks used in the reflector.

Biases between the benchmark model and the actual experiment have yet to be assessed in great detail. It is expected that with the release of additional HTTR data, the benchmark uncertainties will be reduced and appropriate biases and corrections to the benchmark model can be assessed to bring the calculated results into better agreement with the physical experiment. Additional assessment of the impurity levels in graphite may also improve the quality of the benchmark, because of the sensitivity to the boron concentration in the graphite blocks. Selection of graphite for future NGNP reactors should require a thorough examination; the performance and accuracy of future computational models will be inherently driven by the proper characterization of the graphite composition.

Activities beyond completion of this initial benchmark include the ongoing evaluation of the remaining five annular start-up core critical experiments prior to evaluation of the remaining start-up core physics experiments such as measured rod worth, temperature coefficient, and reactivity rates. Future benchmarking activities of the HTTR might include analyses of the hot zero-power critical, rise-to-power tests, and other irradiation, safety, and technical evaluations and experiments.

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