Flattop-HEU Benchmark Reevaluation Summary

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INTRODUCTION

The Flattop critical assembly was first constructed in the 1950's at Los Alamos National Laboratory as a follow-on to the Topsy experiment. Flattop is composed of a sphere of special nuclear material (SNM) surrounded by a thick spherical reflector made of natural uranium (NU). Two SNM cores currently exist: a highly-enriched-uranium (HEU) core and a plutonium core. The reflector is composed of three parts: a stationary hemisphere and two movable quarter spheres. For fine reactivity control, there are three control rods of NU that are inserted into the stationary hemisphere from underneath the assembly. The final components that allow for reactivity adjustment are the glory hole pieces, mass adjustment buttons, and hemispherical caps. These pieces can be loaded in various configurations to change the available reactivity loaded in the system. Many of these components are shown in Figure 1 and 2.

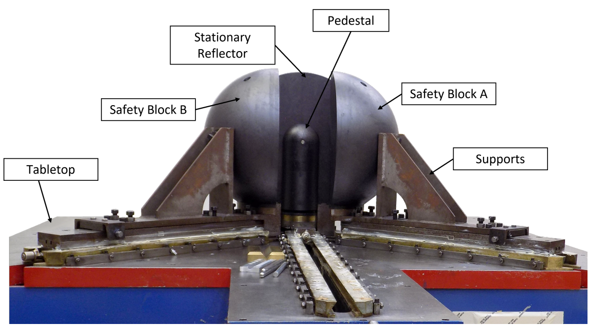

Fig. 1. Flattop with Labelled Components.

While Flattop's original purpose was to benchmark one-dimensional transport codes, today the mission has expanded to include fission and activation product yield measurements, replacement measurements, and nuclear accident dosimetry testing [1]. Flattop is also used to conduct criticality safety training.

In 1999, a critical configuration of Flattop was evaluated and published in the International Criticality Safety Benchmark Evaluation Project (ICSBEP) Handbook [2]. The original benchmark evaluation, named Flattop-HEU, was based on an experiment completed in the 1960's, but the model created was an idealized configuration adjusted by the evaluator to result in an identical k^{eff} value to the experiment [3]. This original evaluation was written to provide two one-dimensional parameters (core and reflector diameters) that defined a critical configuration. The diameters used in this original evaluation were 6.1156 and 24.1242 cm, and the densities used were 18.62 and 19.0 g/cm^3. As the role of benchmark evaluations

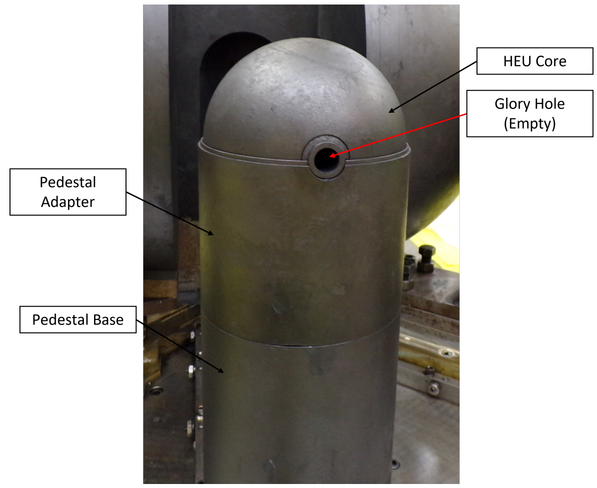

Fig. 2. Flattop Pedestal with Labelled Components.

has expanded beyond use in criticality safety to serving a key role in nuclear data evaluation, a more detailed evaluation is desired[1].

This paper details the final results of a full reevaluation, which was completed after taking new, high-fidelity measurements [4]. The experimental configuration selected for the benchmark evaluation is one commonly used in recent experiment, discussed in detail previously [5]. The paper summarizes the detailed model and the largest contributions to the overall uncertainty. Also discussed are the results of the computational models compared to the experimentally measured and benchmark k_{eff} values.

DETAILED MODEL

Simplifications

In extremely detailed models created for benchmarks, everything in the building is included in the model as it potentially contributes to the reflection of neutrons. For Flattop-HEU, this included the building, Planet, and other equipment in the building. When all of this is modeled as shown in Figure 3, the model becomes extremely complex and computationally expensive. To make the detailed model more universally friendly to various computational codes and to improve computational efficiency, several simplifications were made between reality and the detailed benchmark model. These simplifications, which are biased out of the final results, are listed in Table I along with their individual and cumulative contributions. For each of these simplifications, the component added is added to the model in the previous row. For example, gravity

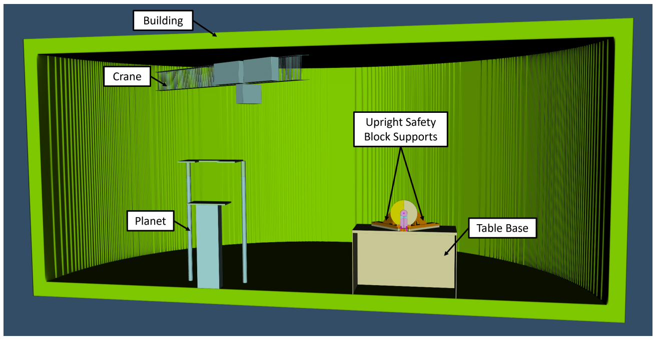

Fig. 3. Cutaway along X=0 Plane of 3D Rendering of Flattop-HEU Model before Simplifications.[6]

TABLE I. Detailed Model Biases from Complex Model in Figure 3.

Model	k_{eff}	Δk	Cumulative Δk
Detailed Model	1.000269	-	-
Add Gravity	1.000240	-0.000029	-0.000029
Add RTDs	1.000243	0.000003	-0.000026
Add Safety Block Supports	1.000291	0.000048	0.000022
Add Table Base	1.000308	0.000017	0.000039
Add Building	1.000341	-0.000018	0.000021
Add Crane	1.000380	0.000072	0.000093
Add Planet	1.000359	-0.000021	0.000072

is added to the detailed model, then the RTDs are added to the model with gravity already applied, and so forth.

Detailed Benchmark Model

The detailed benchmark model for Flattop-HEU is shown in Figure 4 and 5. This model includes all components of the Flattop critical assembly except those biased out previously. The dimensions in this model were a combination of measurements made in June 2022 [4] and engineering drawing values for components that could not be measured. This model was used in the uncertainty and sensitivity analysis discussed in the next section.

UNCERTAINTY ANALYSIS

The sensitivity effects for the benchmark measurement case examined were evaluated using Monte Carlo N-Particle®[1] (MCNP®) Version 6.3.0 [7] and ENDF/B-VIII.0 [8] neutron cross section libraries. With the introduction of MCNP6.3, there was the addition of another digit (tenth of a pcm) on the value of k_{eff} reported. Throughout this summary, the pcm value is provided in parenthesis for ease of reading. This is not the uncertainty on the reported value. The calculations were run to a statistical uncertainty of ±0.000019 (1.9) or ±0.000018 (1.8).

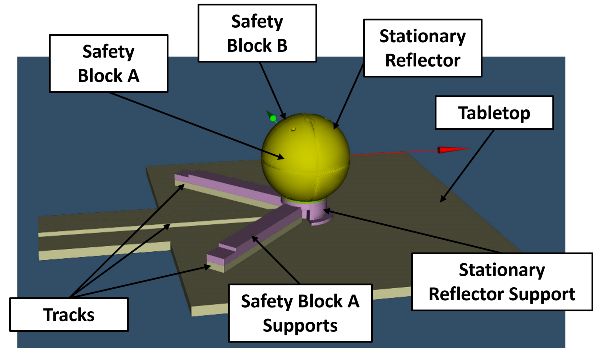

Fig. 4. 3D Rendering of Flattop-HEU Detailed Benchmark Model. [6]

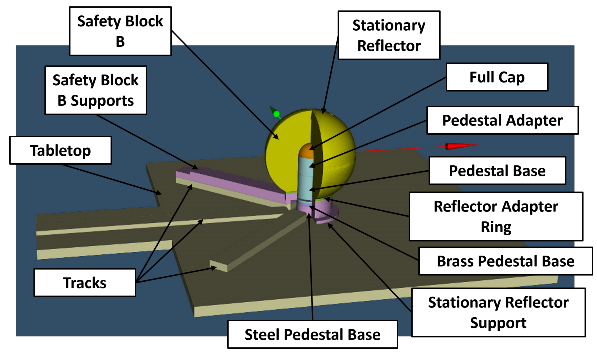

Fig. 5. 3D Rendering of Flattop-HEU Detailed Benchmark Model with Safety Block A Removed. [6]

The uncertainties affecting the experiment have been divided into six categories: critical measurement, mass and density, dimensions, material compositions, positioning, and temperature. Each category is considered separately and later combined to compute the total experiment uncertainty. The uncertainty analysis was completed using a combination of adjoint-based sensitivity methods [9] (for categories: mass and composition) and direct perturbation (for all other categories). If the final $u_{k,i}$ is less than 0.000005 (0.5), the uncertainty is judged to be negligible. This section summarizes the overall experimental uncertainty by examining the non-negligible contributions to each category.

Criticality Measurement

The reactivity of the experiment is calculated based on the measured asymptotic reactor period, which is input into the Inhour equation,

$$\rho = \frac{\Lambda}{T\beta_{eff}} + \sum_{i=1}^{P} \frac{\beta_i/\beta}{1+\lambda_i T} \tag{1}$$

where: ρ is the reactivity in dollars, $\beta_{\text{eff}}/\Lambda$ is the absolute value of the Rossi-α at delayed critical, β_{eff} is the effective

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delayed neutron fraction, Λ is the prompt neutron lifetime of the system in s, T is the reactor period in s, β_i/β is the relative abundance of the precursor group i, λ_i is the decay constant of precursor group i in s^{-1}, and P is the number of delayed neutron precursor groups (twelve in the case of Flattop-HEU). Once the reactivity is calculated, the k_{eff} of the system can be calculated using:

$$k_{eff} = \frac{1}{1 - \rho\beta_{eff}}. \quad (2)$$

The sources of uncertainty in this measurement include: numerical fit of the reactor period, reproducibility, and delayed neutron parameters. When all of these sources are considered together, the overall uncertainty in the k_{eff} of the system for the criticality measurement is ± 0.000030 (3.0).

Mass

The uncertainty of the total mass of N components is

$$u_T = \sqrt{Nu_r^2 + N^2u_s^2 + \frac{Nr_r^2}{12}}, \quad (3)$$

where u_T is the uncertainty of the total mass, u_r is the random mass measurement uncertainty, u_s is the systematic mass measurement uncertainty, and r_r is the round-off resolution, N is the total number of components in the element, when each one has been measured separately. The scales used for these measurements all have a reported random mass measurement uncertainty (u_r) of 0, provided by the calibration certificates. Some components not weighed in the June 2022 measurement campaign; therefore, the masses of those components were based upon historical measurements. The relative sensitivity for the mass of each component was obtained using the iterated fission probability method in MCNP6.3, implemented in the KOPTS and KSEN cards. Table II provides the non-negligible mass uncertainties for the Flattop-HEU experiment.

TABLE II. Flattop-HEU Mass Uncertainty Contributions.

Component	k_{eff} Uncertainty
HEU Core	± 0.000649 (64.9)
Full Cap	± 0.000008 (0.8)
NU Mass Adjustment Button	± 0.000011 (1.1)
Stationary Reflector	± 0.000324 (32.4)
Safety Block A	± 0.000450 (45.0)
Safety Block B	± 0.000450 (45.0)
Control Rod E	± 0.000012 (1.2)
Control Rod F	± 0.000034 (3.4)
Control Rod G	± 0.000006 (0.6)

Dimension

The dimensions for the components of Flattop are a combination of measured and drawing values. The sensitivity coefficients for the components were obtained by varying the individual dimensions separately, while the density was adjusted to conserve the mass of the component. When a tolerance from a drawing or historical evidence was used as the uncertainty, it was considered to be bounding. When a recent, high-fidelity measurement was used, the uncertainty from the measurement technique was used. The non-negligible dimension uncertainties for the Flattop-HEU experiment are provided in Table III.

TABLE III. Flattop-HEU Dimension Uncertainty Contributions.

Component	k_{eff} Uncertainty
HEU Core	± 0.000086 (8.6)
Full Cap	± 0.000013 (1.3)
HEU Mass Adjustment Button	± 0.000010 (1.0)
Glory Hole Filler Pieces	± 0.000011 (1.1)
Stationary Reflector	± 0.000018 (1.8)
Safety Block	± 0.000013 (1.3)
Control Rod	± 0.000008 (0.8)
Reflector Sleeve	± 0.000011 (1.1)
Pedestal Adapter	± 0.000038 (3.8)
Pedestal Base	± 0.000017 (1.7)
NU Mass Adjustment Button	± 0.000007 (0.7)
Reflector Adapter Ring	± 0.000006 (0.6)
Lifting Fixture Plug	± 0.000013 (1.3)
Brass Pedestal Base	± 0.000023 (2.3)
Stationary Reflector Base	± 0.000005 (0.5)
Safety Block Spacer	± 0.000010 (1.0)
Steel Pedestal Base	± 0.000016 (1.6)
Safety Block Supports	± 0.000014 (1.4)
Tracks	± 0.000007 (0.7)

Composition

The composition uncertainties for Flattop-HEU were calculated using adjoint-based sensitivity methods [9]. For the HEU, the isotopic breakdown of uranium was provided for most components. NU isotopics were not reported, but some smaller parts were evaluated and an average composition was created. For both types of uranium, no impurity data was supplied. As such, the average impurities from the Jemima plates were calculated and scaled to a per ^{235}U atom basis. These were then applied to Flattop-HEU compositions on a per ^{235}U atom basis. As this is a bounding simulation, the final uncertainty for that calculation was scaled appropriately. The uncertainty due to impurities in uranium along with the other composition uncertainties in Flattop-HEU are provided in Table IV.

Positioning

The positioning uncertainty for Flattop-HEU can be broken into several sub-categories: safety block gap, control rod insertion, glory hole piece alignment, reflector sleeve insertion, and pedestal seated position. The positioning of components was aided by bolts, pins, and interlocking features. However, there was still the possibility that components could move

TABLE IV. Flattop-HEU Composition Uncertainty Contributions.

Components	k_{eff} Uncertainty
Uranium Impurities	± 0.000032 (3.2)
HEU Core	± 0.000257 (25.7)
Full Cap	± 0.000014 (1.4)
Pedestal Adapter	± 0.000033 (3.3)
Pedestal Base	± 0.000009 (0.9)
Stationary Reflector	± 0.000111 (11.1)
Safety Block A	± 0.000065 (6.5)
Safety Block B	± 0.000064 (6.4)
Control Rod F	± 0.000010 (1.0)

either individually or in a combined state. This possible movement was evaluated, and all of the uncertainty contributions for the positioning combined to a total of ± 0.000069 (6.9).

Total Uncertainty

When all of these uncertainties are considered, and the sum of squares is taken for the uncertainty, the total uncertainty of the experiment is calculated. The total uncertainty is ± 0.001019 (101.9). This value is smaller than that of the original benchmark evaluation, which is ± 0.0030 (300) [3], and smaller than the preliminary benchmark reevaluation, which was quoted as ± 0.00157 (157) with an uncertainty of +100%/-0% [10]. Additionally, this uncertainty value is on the same order of magnitude as modern benchmark evaluations.

CONCLUSIONS

Flattop-HEU is a critical assembly made of a sphere of HEU surrounded by a thick NU reflector. This experiment was originally evaluated as a benchmark in 1999, and a reevaluation effort began in 2022 with new high-fidelity measurements. The goal of this reevaluation was to better characterize the uncertainty of the assembly, which was achieved. The experimental and benchmark model k_{eff} values and their associated uncertainties and biases are listed in Table V for the detailed model. Additionally, a comparison between the benchmark model and the detailed model is provided in Table VI.

TABLE V. Summary of Experimental and Benchmark k_{eff}, Uncertainty, and Bias for the Detailed Model.

Experiment k_{eff}	Experiment Uncertainty	Simplification Effects	Benchmark Model k_{eff}
1.001510	± 0.001019	0.000072 ± 0.000070	1.001438 ± 0.001021

TABLE VI. Sample Calculation Results for the Detailed Model.

Benchmark	MCNP 6.3 ENDF/B-VIII.0	C-E (pcm)
1.001438 ± 0.001021	1.000269 ± 0.000018	-116.9

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