

Zeus: Fast-Spectrum Critical Assemblies with an Iron-HEU Core Surrounded by a Copper Reflector

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Abstract

Experiments to investigate critical systems of iron moderated highly enriched uranium in the intermediate-energy range were attempted. However, due to size limitations, the systems fell into the fast-energy range. Two critical configurations were established with a uranium mass of ~ 198 kg and a Fe/²³⁵U Ratio of ~15. Experimental uncertainties were systematically evaluated to estimate their effect on multiplication. The combined uncertainty for these experiments is estimated to be $\pm 0.0024 \Delta k_{eff}$. Consequently, both Zeus iron configurations are judged to be acceptable for use as criticality-safety benchmark experiments.

KEYWORDS: Comet, copper reflected, critical experiments, cylinder, fast spectrum, highly enriched uranium, iron moderator, metal, Zeus

1. Overview of Experiments

Two Zeus experiments were assembled at the Los Alamos Critical Experiment Facility (LACEF) at Los Alamos National Laboratory (LANL) in 2002. Criticality was first achieved on October 8, 2002. After modifications to the assembly, criticality was again achieved on October 10, 2002.

The Zeus experiments are designed as a series of critical assemblies that produce variable spectra. This set of experiments was intended to test the adequacy of iron cross-sections in the intermediate-energy range. However, due to limitations on size, the assembly actually fell into the fast-energy range, as discussed under Spectral Characteristics.

Plates of highly enriched uranium (HEU) metal were interspersed with carbon steel plates in a cylindrical stack completely surrounded by a copper reflector. This configuration was dubbed the “4-1-4 Iron Core,” as each unit consisted of four (4) iron plates, one (1) HEU plate, and four (4) iron plates. While no change was made to the basic fuel unit between configurations, the top row of the side reflector and the aluminum shim in the lower half of the assembly were removed from Configuration 1 to produce Configuration 2. A summary of the Zeus configurations is shown below.

Table 1. Summary of Critical Configurations.

Configuration	U Critical Mass [g]	Fe/ ²³⁵ U Ratio
1 and 2	198,234.5	14.9:1

Based on this evaluation, both Zeus iron configurations are judged to be acceptable for use as criticality-safety benchmark experiments.

2. Description of Experimental Configurations

2.1 General Description - The Zeus experiments were assembled on the general-purpose Comet vertical assembly machine at LACEF. The assemblies consist of a cylindrical core region containing interspersed plates of HEU metal and carbon steel that are surrounded on all sides by a metallic copper reflector. The same plates were used in both experiments.

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The assembly is divided into two portions. The upper part of the reflector, which includes the upper, corner, and side reflectors, rests on a stationary aluminum support plate (Top Plate) attached to the Comet machine. The upper segment of the core rests on a thin, square stainless steel plate, called the diaphragm, which is supported by copper corner reflectors. The remainder of the core and the lower reflector are seated on a circular aluminum platen adapter plate connected to the vertical drive (ram) of the assembly machine. The lower core plates and the lower reflector are held in position by a central, hollow aluminum alignment tube. The experiment is assembled by raising the lower portion into the reflector until it fully closes to the steel diaphragm that supports the upper segment of the core. There are no other control, safety, or shim rods inside the assembly.

A photograph of the Zeus assembly on the Comet machine is shown in [Figure 1](#). The bottom copper reflector and two moderator plates can be seen resting on the platen adapter plate. The central alignment tube also is clearly visible. The lower segment of the core is pictured in

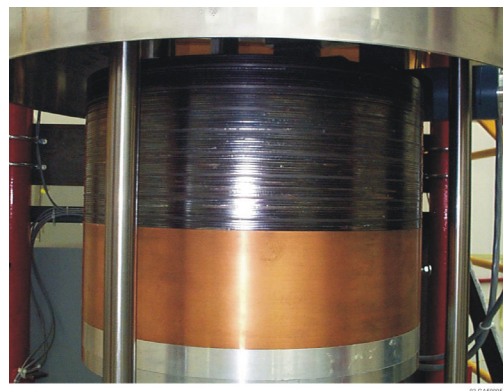
Figure 2.

Zeus was located in a Critical Assembly and Storage Area (CASA). The assembly was approximately 6 feet above a 6-inch thick concrete floor. The 5-inch thick concrete ceiling was located 14 feet above the assembly. Three 15-inch thick concrete walls were approximately 8, 12, and 40 feet from the assembly. One 20-inch concrete wall was approximately 20 feet from the assembly.

Figure 1. The Zeus Assembly Mounted on the Comet Machine.



Figure 2. Lower segment of the Zeus 4-1-4 Iron Core.



2.2 Core Region – The main core constituents are HEU and carbon steel plates. Other core components include the steel diaphragm plate that supports the upper core and the hollow aluminum tube that aligns and stabilizes the plates in the lower portion of the core. A thin aluminum shim plate was also used in the first experiment.

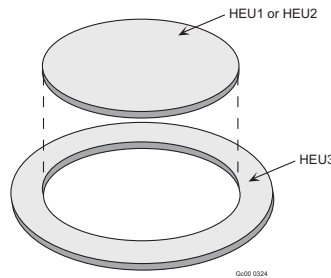
Tolerances for the outer diameter and thickness of the HEU1 and HEU2 plates are $+0.000/-0.005$ in., and ± 0.002 in., respectively. Tolerance for the inner diameter of the HEU2 plates is $+0.005/-0.000$ in.

The CS1 plates are nominally 0.120 in. thick, with a 21.00 in. outer diameter. The CS2 plates are nominally 0.120 in. thick with an outer diameter of 21.00 in. and an inner diameter of 2.50 in. Tolerances for the carbon steel plates are $+0.00/-0.02$ in. on the outer diameter and $+0.02/-0.00$ in. on the inner diameter. The thickness of the carbon steel plates is 11 gauge, nominally 0.120 in. Experimenters measured the stack height of the plates used in the assemblies. The plates were stacked in order, and measurements were made of four plates together (comprising half of a Unit). The uncertainty in the measured height for each stack is less than 0.005 in.

The HEU fuel plates in the Zeus assembly have a long history of use in LANL experiments. The type HEU1 plates (with no internal holes) along with similar plates with a 1.5-inch-diameter central hole were manufactured at Los Alamos Scientific Laboratory (now LANL) in the mid 1950s and used there in the Jemima experiments (IEU-MET-FAST-001). The type HEU3 annular rings were manufactured later at Oak Ridge and used with the smaller plates in the Super Jemima experiments at LANL. In the late 1960s, some of the inner plates were modified to incorporate larger central holes and, along with modified outer rings, were used in the Big Ten experiments (IEU-MET-FAST-007) performed in the 1970s and again in the early 1990s.

The fuel plates were manufactured so that they would form tightly nested pairs (one plate inside another as shown in Figure 3) with a HEU1 or HEU2 plate on the inside and an annular HEU3 plate on the outside. The resulting combined fuel plates have essentially the same inner and outer dimensions as the core carbon steel plates.

Figure 3. A Nested Pair of HEU Fuel Plates.



The alignment tube can be adjusted vertically. It is positioned such that it is flush with the bottom of the diaphragm when the assembly is fully closed.

2.3 Reflector Region – The copper reflector components include the upper, lower, corner, and side reflector sections. The lower reflector and the lower core are supported by an aluminum platen adapter plate that attaches to the platen and Comet vertical drive.

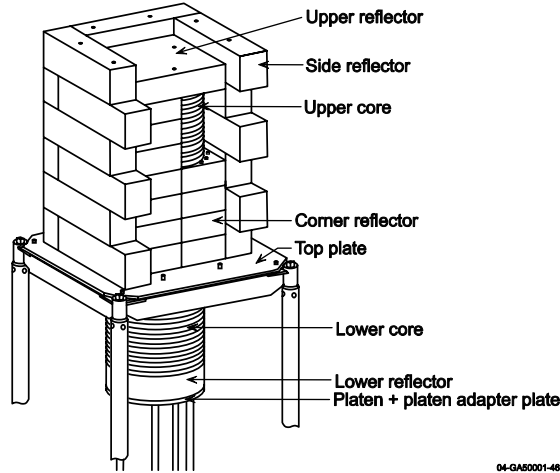
Except for a small central hole, the top reflector is a square parallelepiped that rests on the four uppermost corner reflector pieces. The corner reflector pieces are shaped so that they closely surround the circular core plates and produce a rectangular exterior that aligns with the inner planar surfaces of the side reflector pieces. The lower reflector piece is a cylinder that supports the lower core plates. It, in turn, rests on the aluminum platen adapter plate that is secured to the platen and Comet vertical drive assembly. The top plate supports the copper reflector and the upper core.

Tolerances for the bottom reflector and the side reflector pieces are ± 0.01 in. on all dimensions. Tolerances on the top reflector are ± 0.005 in. on the inner diameter and $+0.00/-0.01$ in. on the outer

dimensions. Tolerances on the corner reflector pieces are ± 0.01 in. on the height and radial dimensions and $+0.00/-0.01$ in. on the side dimensions.

The schematic cutaway of the Zeus assembly shown in Figure 4 shows the relationship between the core and reflector pieces.

Figure 4. Schematic Cutaway of Zeus before Assembly.



2.4 First Configuration – For the first configuration, HEU and carbon steel plates were arranged to produce a Fe/²³⁵U ratio of approximately 14.9:1 with a critical uranium mass of 198.2 kg.

For the first core loading of Zeus, a unit cell (repeating pattern) of one HEU plate sandwiched in the middle of eight carbon steel plates was selected. Criticality was achieved with 16 units on October 8, 2002. When fully assembled, the configuration was determined to be critical on the source (power increasing linearly, rather than exponentially).

A schematic of the standard unit cell is shown in Figure 5. Figure 6 depicts the unit cell immediately below the diaphragm (SD), which includes aluminum shim and spacer plates. There is a small gap between the top carbon steel plate and the upper reflector (See Figure 7.). Based on the measured height of the carbon steel plates and the nominal dimensions of all other pieces, this gap is 0.204 cm.

Figure 5. Schematic of the Standard Unit Cell of Both Assemblies (with nominal dimensions).

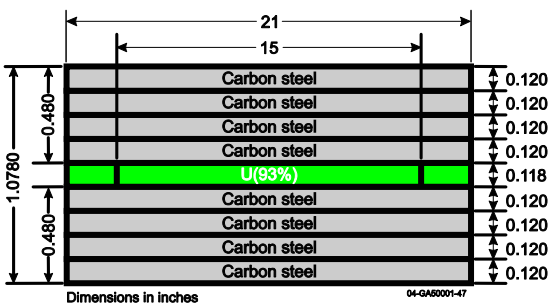


Figure 6. Unit Cell Immediately Below the Steel Diaphragm in the First Assembly (with nominal thicknesses for carbon steel plates).

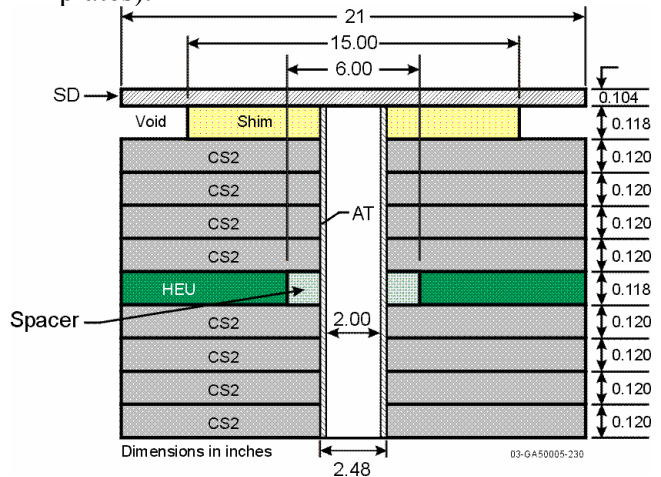
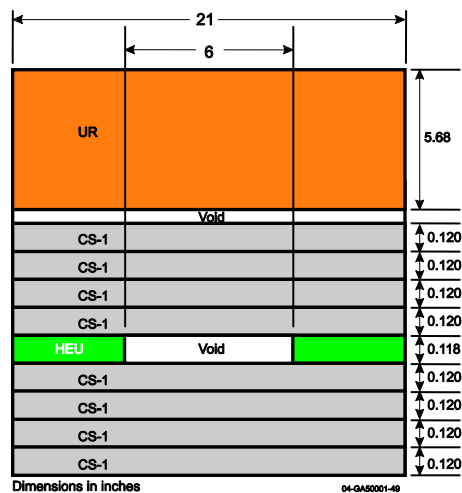


Figure 7. Uppermost Unit Cell (with nominal thicknesses for carbon steel plates).

2.5 Second Configuration – For the second configuration, the aluminum shim was removed along with the top row of side copper reflector. Other than the removal of the shim, the core remained the same. A schematic of the standard unit cell is shown in Figure 5.

This configuration was slightly supercritical, with a period of approximately 61.4 seconds. That period corresponds to approximately 13.7β (β_{eff} of 0.0068, using the GODIVA In-Hour Equation) of excess reactivity and therefore to a value of k_{eff} very near 1.0009.

3. EVALUATION OF EXPERIMENTAL DATA

The results of sensitivity studies performed to determine the effects of various uncertainties in the reported experimental data on the values of k_{eff} are reported in this section. Calculations were performed using full three-dimensional MCNP4C^a models with continuous-energy cross sections based (primarily) on ENDF/B-VI release 4 (ENDF/B-VI.4). The MCNP calculations employed 1,250 generations of neutrons, with 5,000 histories per generation. The first 50 generations were excluded from the statistics for each case, producing 6,000,000 active histories in each calculation. Sensitivity studies were performed to determine the effect of the inner diameter (2.51 in.) dimension in the lower core. Reducing the diameter to 2.5 in. was determined to be a negligible effect (-0.0001 ± 0.0003). Thus, in the detailed model 2.5 in. is used for the inner diameter in the lower core. The total experimental uncertainty is sufficiently small to judge these experiments acceptable for use as benchmarks.

3.1 Material Mass – Because the bulk densities for the benchmark model are calculated from the material masses and the nominal dimensions for the pieces, an uncertainty in the reported mass is manifested as an uncertainty in the corresponding atom density. Sensitivity calculations were performed to determine the change in k_{eff} for a change in mass for uranium, carbon steel, and copper components. These calculations changed the density while keeping constant dimensions.

Relative uncertainties for the total mass of HEU and carbon steel were calculated to be $\pm 0.03\%$ and $\pm 0.03\%$, respectively. Results of multiple measurements on the copper pieces yielded standard deviations significantly less than two pounds. For the sensitivity analysis, an absolute 1σ uncertainty

^a Judith F. Briesmeister, ed., “MCNP™ - A General Monte Carlo N-Particle Transport Code, Version 4C,” Los Alamos National Laboratory report LA-13709-M (March 2000).

of 1 pound for these measurements is assumed, which propagates to an expected relative uncertainty on the total copper mass of $\pm 0.40\%$.

The uncertainties in k_{eff} were calculated from the estimated relative scale uncertainties and the results from the sensitivity calculations. The resulting standard uncertainties are shown in Table 2 below.

3.2 ^{235}U Enrichment – The average ^{235}U enrichment provided was calculated to be 0.932190 ± 0.000162 with a corresponding relative standard deviation of 0.000174. Sensitivity calculations were performed to determine the uncertainty in k_{eff} for a relative change of $\pm 0.0174\%$ in ^{235}U enrichment. For these calculations, the increase in the ^{235}U weight fraction was compensated by a corresponding decrease in the ^{238}U weight fraction. Minor isotopes remained unchanged. The resulting Δk_{eff} due to uncertainties in the enrichment measurements was calculated to be ± 0.0003 , and enrichment uncertainty is therefore considered negligible.

3.3 Material Dimensions – All of the dimensional sensitivity calculations adjusted the material density homogeneously to maintain a constant material mass.

3.3.1 HEU Plates – An original drawing for the type HEU3 plates could not be located, and, therefore, the specified tolerances are not known. (The tolerance for the outer diameter of the Type HEU1 and HEU2 plates was $+0.000/-0.005$ in.). However, an undated inspection report shows a “Min.” and “Max.” I. D., O. D., and thickness for each of the type HEU3 plates. It should be emphasized that these are not true global maximum and minimum plate diameters but rather local measurements of maximum and minimum dimensions for each plate.

MCNP4C calculations were performed to assess the uncertainty due to the height of the HEU plates. The averages of the measured maximum and minimum thicknesses are, respectively, 0.120 in. and 0.115 in. Two MCNP4C calculations were run, one with an HEU plate thickness of 0.120 in. and the other with an HEU plate thickness of 0.115 in. The difference in k_{eff} between the two calculations was ± 0.0004 (± 0.0003).

3.3.2 Carbon Steel Plates - Sensitivity calculations were performed with MCNP4C to determine the effect of the thickness of the carbon steel plates on k_{eff} . The standard deviation of the average measured stack heights was calculated to be 0.010400 cm. Dividing by 4 yields the thickness (0.002600 cm) increment/decrement applied to each carbon steel plate. Mass of each plate was conserved. The corresponding changes in k_{eff} were found to be ± 0.0021 (± 0.0003). Clearly, the effect is not negligible.

3.4 Combined Uncertainty – The only significant experimental uncertainties in k_{eff} are those identified below. Therefore, the combined experimental uncertainty is ± 0.0024 (± 0.0008) Δk_{eff} for both Zeus experiments. Modeling uncertainties are shown and described later.

Table 2. Summary of Experimental Uncertainties.

Source of Uncertainty	Expected Parameter Variation	Δk_{eff} for Expected Parameter Variation (1σ)
Material Mass		
HEU Mass	$\pm 0.03 \%$	± 0.0002 (± 0.0003)
Carbon Steel Mass	$\pm 0.03 \%$	± 0.0001 (± 0.0003)
Copper Mass	$\pm 0.40 \%$	± 0.0010 (± 0.0003)

Table 2. Summary of Experimental Uncertainties (Continued).

Source of Uncertainty	Expected Parameter Variation	Δk_{eff} for Expected Parameter Variation (1σ)
Material Dimensions		
HEU Plates	+ 0.002 in. – 0.003 in.	± 0.0004 (± 0.0003)
Carbon Steel Plates	± 0.0026 cm	± 0.0021 (± 0.0003)
HEU Composition		
^{235}U wt. %	± 0.0174 wt. % (See Sec. 2.2)	± 0.0003 (± 0.0003)
Total Uncertainty		± 0.0024 (± 0.0008)

3.5 Spectral Characteristics – Calculations were performed to determine the energy regime of the ZEUS 4-1-4 Iron Core. This configuration is considered a fast system based upon the predominance of fissions occurring at neutron energies above 100 keV.

Table 3. MCNP – ENDF/B-VI.4 Neutron Flux and Fissions

Average Neutron Flux, %		
< 0.625 eV	0.625 eV – 100 keV	> 100 keV
0.00 ± 0.00	17.93 ± 0.22	82.07 ± 0.12
Average Fissions, %		
< 0.625 eV	0.625 eV – 100 keV	> 100 keV
0.00 ± 0.00	27.53 ± 0.24	72.47 ± 0.12

4. BENCHMARK SPECIFICATIONS

4.1 Description of Models – The ideal configuration that the designer of the Zeus experiments envisioned is a cylindrical column of identical, repeating vertical units surrounded by a reflector region.^a For these experiments, each repeating unit contains a plate of HEU with carbon steel plates above and below it, and the reflector is copper. Both configurations contain 16 repeating units of one HEU plate with 4 plates of carbon steel above and below it. The benchmark models described below are a compromise between the experimenter's ideal configuration and the physical configuration that produced a critical condition. Whenever it is possible to do so without having an important effect on reactivity, the neutron spectrum, or the spatial shape of the flux, the benchmark model modifies the actual physical configuration to conform to the ideal one.

The development of the benchmark models began with the construction of a very detailed model of each actual critical configuration with the MCNP4C Monte Carlo code. These models represent each carbon steel plate, each inner HEU ring, each outer HEU annulus, and each copper piece individually. The models also contain the diaphragm, the platen, the alignment tube, and the top plate. In addition, the first configuration contains the aluminum shim. The second configuration removes the shim plate and the top row of side copper reflector.

The detailed models contain three additional approximations and assumptions. First, screws and screw holes were ignored. Because the screws were made of the same material as the piece into which they were inserted and because they fit very tightly, this approximation is judged to have an insignificant effect on reactivity. Second, impurities and ^{234}U , ^{236}U , and ^{238}U concentrations were not available for all of the HEU pieces. In such cases, the average concentrations from similar pieces were used in place

^a Personal communication, Peter J. Jaegers, May 2000.

of the missing information. Finally, a single density was used for all of the copper corner reflector pieces, and a single (but slightly different) density was used for all of the copper side reflector pieces. All of the corner reflector pieces were made from a single block of copper, and the side reflector pieces all came from a single copper casting. Consequently, it was felt that the average density is more representative than the piece-by-piece densities based on individual measurements.

The detailed models also ignore the effects of room return. As can be seen from Figure 1, and as stated earlier, the Comet assembly machine is quite some distance from the walls, floor, and ceiling of the building. Room return effects were calculated using the benchmark model surrounded by 20 inch thick concrete walls, floor, and ceiling all located 6 feet from the assembly. The change in k_{eff} was calculated to be -0.0001 ± 0.0004 . Consequently, it is clear that room return can be ignored.

The development of the benchmark models thereafter proceeded in a series of sequential steps. The sensitivity studies that are described below were conducted in a sequence such that, at each step, none of the preceding modifications were retained. Thus, the effects must be summed in order to estimate the cumulative effect.

The MCNP4C calculations all employed 6,000,000 active histories. All of the calculations were performed with uranium cross sections derived from ENDF/B-VI.4. The aluminum and iron cross sections were derived from ENDF/B-VI.2.

4.1.1 Material Simplifications – A number of material simplifications have been made to reduce the complexity of the benchmark model. Simplifications can be subdivided into two categories, removing impurities and replacing densities of individual pieces with an average density for that material.

Impurities in the carbon steel have a substantial effect on reactivity, primarily from scattering/moderation. However, replacing four individual carbon steel plates (half of a unit) with one plate of equal mass and average impurities, for plates with holes and solid plates as appropriate, is considered a negligible effect on reactivity.

The copper pieces contain tiny amounts of iron, chromium, and silver. Calculations with MCNP4C demonstrated that these impurities have negligible impact on reactivity and the impurities are omitted in the benchmark model.

Uranium parts contain residual amounts of carbon, aluminum, silicon, iron, chromium, nickel, and magnesium. Removing these impurities has a small reactivity effect. However, homogenizing the fuel plates and using the average impurities therein results in a negligible effect on reactivity. Therefore, the fuel plates were homogenized with the average impurities therein. The results from these calculations are shown below.

Table 4. Reactivity Effect of Material Simplifications.

Simplification	Δk_{eff}
	Configuration 1
Remove impurities from carbon steel	-0.0026 (± 0.0004)
Replace 4 individual CS plates with one plate equal in height and mass, and average impurities for CS1 and CS2 type plates.	-0.0005 (± 0.0004)
Remove impurities from copper	-0.0003 (± 0.0004)
Remove impurities from HEU	-0.0007 (± 0.0004)
Replace individual HEU plate-and-ring combinations with homogeneous plate containing average impurities	-0.0005 (± 0.0004)

4.1.2 Geometry Simplifications – There are three major differences between the ideal benchmark envisioned by the experimenter and the actual critical configurations: the structural components of the Comet assembly machine, the steel diaphragm that supports the upper portion of the core, and the central holes in the units below the diaphragm. There also are some differences, such as the presence of the platen/platen adapter plate, the alignment tube, aluminum shim and spacer, and the hole in the top reflector, which depart from the ideal. The results from the sensitivity studies that address the geometric modifications to arrive at the benchmark models are summarized below.

Table 5. Reactivity Effect of Geometry Simplifications.

Simplification	Δk_{eff}
	Configuration 1
Remove Top Plate	0.0000 (\pm 0.0004)
Remove Diaphragm	-0.0015 (\pm 0.0004)
Remove Alignment Tube	-0.0009 (\pm 0.0004)
Remove Platen and Platen Adapter Plate	-0.0036 (\pm 0.0004)
Fill hole in Upper Copper Reflector	0.0000 (\pm 0.0004)

First, the Top Plate was removed. MCNP4C calculations indicated no change in reactivity.

Removal of the diaphragm decreases reactivity. The principal reason for the decrease is reduction in scattering/moderation in a high importance region. As indicated above, this change is statistically significant and cannot be ignored.

Eliminating the alignment tube results in a statistically significant reduction in k_{eff} . Removal of the platen/platen adapter plate is an even greater effect. These elements cannot be eliminated justifiably.

Filling the hole in the upper reflector is considered a negligible simplification.

The small annular gap between the cylindrical core and the surrounding reflector also will be retained, because it provides a streaming path for neutrons. The reactivity effect of eliminating it has not been quantified.

Thus, the benchmark model will differ from the detailed model by removing the Top Plate and filling the hole in the Upper Reflector. Impurities will be removed from the copper reflector. The HEU fuel plates will be homogenized using the average impurities of the fuel unit. Finally, the carbon steel plates will be simplified as described above. Taken together, these changes produce a somewhat less complex model of the experiment without a significant net change in reactivity.

4.1.4 Temperature Data – The temperature of the first core was reported to be 20.9°C. The temperature of the second core was about the same as the first. Consequently, calculations that employ cross sections at 20°C are perfectly adequate for these benchmarks.

4.2 Experimental and Benchmark-Model k_{eff} – The first configuration was determined to be critical on the source. Consequently, for the purposes of this evaluation, the actual experiment can be considered to be exactly critical with an experimental k_{eff} of 1.0. The second configuration was slightly supercritical with a period of 61.4 seconds. That period corresponds to approximately 13.7¢ of excess reactivity (β_{eff} of 0.0068, using the GODIVA In-Hour Equation) and therefore to a value of k_{eff} very near 1.0009. Results from calculations with MCNP4C and nuclear data derived primarily from

ENDF/B-VI.4 are given below. Due to only slight modifications from configuration 1 to configuration 2, the experiments are highly correlated.

Table 6. Calculated Results for Detailed and Benchmark Models to Obtain Bias.

Model		Detailed	Benchmark
1 st Configuration	k _{eff}	1.0074 ± 0.0003	1.0065 ± 0.0003
	Δk	-	-0.0009 ± 0.0004
2 nd Configuration	k _{eff}	1.0084 ± 0.0003	1.0077 ± 0.0003
	Δk	-	-0.0007 ± 0.0004

The observed biases of $-0.0009 \pm 0.0004 \Delta k$, and $-0.0007 \pm 0.0004 \Delta k$, incorporate the cumulative changes and uncertainties introduced by the material and geometry simplifications that produce the benchmark model. The sensitivity studies reported above produce an uncertainty of $\pm 0.0024 \Delta k$ for both configurations. The uncertainty from the benchmark simplifications is $\pm 0.0004 \Delta k$ for both experiments. When the two uncertainties are combined, the resulting uncertainty is $\pm 0.0024 \Delta k$. The benchmark-model k_{eff}'s therefore are 0.9991 ± 0.0024 for the first Zeus Iron-HEU Core benchmark and 1.0002 ± 0.0024 for the second. Results are summarized below.

Table 7. Final k_{eff} Results

k _{eff}	Experiment	Benchmark Model
1 st Configuration	1.0000	0.9991 ± 0.0024
2 nd Configuration	1.0009	1.0002 ± 0.0024

5. RESULTS OF SAMPLE CALCULATIONS

Results from MCNP4C with various libraries are presented below.

Table 8. Results of Sample Calculations.

Codes (Cross-Section Library)→ Case ↓	MCNP (ENDF/B-V) ^(a)	MCNP (ENDF/B-V) ^(b)	MCNP (ENDF/B-VI.2) ^(c)	MCNP (ENDF/B-VI.4) ^(d)
1 st Configuration (Benchmark Model)	1.0043 ± 0.0003	1.0060 ± 0.0003	1.0064 ± 0.0003	1.0065 ± 0.0003
2 nd Configuration (Benchmark Model)	1.0054 ± 0.0003	1.0067 ± 0.0003	1.0077 ± 0.0003	1.0077 ± 0.0003

- (a) 26000.55c cross-section for iron. XXXXX.49c cross-sections for uranium isotopes.
- (b) XXXXX.60c cross-sections for iron isotopes. XXXXX.50c cross-sections for uranium isotopes.
- (c) XXXXX.60c cross-sections for both iron and uranium isotopes.
- (d) XXXXX.60c cross-sections for iron isotopes. XXXXX.49c cross-sections for uranium isotopes.