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Analysis of the Unmoderated Zeus Critical Experiment

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Abstract

The first four Zeus experiments were designed to test the adequacy of ^{235}U cross sections in the intermediate-energy range. The unmoderated Zeus experiment discussed herein has the same general configuration as its predecessors but produces a fast spectrum because it contains no moderator. It therefore constitutes an upper-energy endpoint for the first set of Zeus experiments.

The MCNP5 Monte Carlo code was used to construct a detailed model of the experiment and to assess the reactivity impact of experimental uncertainties. Results from calculations for that model with four different nuclear data libraries are presented. All of the calculated results differ from the experimental value of k_{eff} by at least three standard deviations. However, two of them, JENDL-3.3 and ENDF/B-VII β-2, produce excellent agreement with the experimental value when their cross sections for copper are replaced with ENDF/B-V data. Therefore, it is strongly recommended that the fast cross sections for copper be reviewed prior to the first formal release of ENDF/B-VII.

A simplified benchmark model of the experiment also was developed, and the specifications for it are included as an Appendix. It is shown that this benchmark model retains the reactivity, spectrum, and other important characteristics of the detailed model.

KEYWORDS: Zeus, benchmark, unmoderated, HEU, copper

1. Introduction

The first set of Zeus experiments was designed to test the adequacy of ^{235}U cross sections in the intermediate energy range. The first four Zeus experiments [1-4] achieved intermediate spectra by inserting graphite platters for moderation between platters of highly enriched uranium (HEU). The unmoderated Zeus experiment discussed herein has the same general configuration as its predecessors but contains no graphite and therefore has a fast spectrum. Consequently, it constitutes an upper-energy endpoint for the first set of Zeus experiments.

2. Description of the Experiment

The unmoderated Zeus experiment and its predecessors were performed on the Comet vertical assembly machine at the Los Alamos Critical Experiments Facility between 1999 and 2002. The cylindrical cores contained circular platters of HEU, with or without graphite plates between them,

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and were reflected by copper pieces whose shape produced a rectangular exterior. Most of the reflector pieces were stacked on a tabletop, and the upper part of the core was supported by a steel diaphragm inserted between pieces of the reflector. The bottom reflector and the lower part of the core were attached to a vertical ram. Criticality was achieved by driving the ram upward until the top plate in the lower part of the core came into direct contact with the diaphragm. A hollow alignment tube ensured that the lower plates remained in place during closure. A cut-away schematic of a generic Zeus configuration, with many more plates than in the unmoderated experiment, is shown in Fig. 1.

The configuration of the unmoderated Zeus experiment discussed herein achieved initial criticality on January 8, 2001, with eight HEU platters. There were four platters above the diaphragm and four below it. The circular HEU platters are slightly less than 0.3 cm thick, and all of them have two components, an inner disk with an outer radius of 19.05 cm and a tightly fitting outer annulus with an outer radius of 26.67 cm. The inner disks in the top four plates are solid HEU, but those in the bottom four have a circular central cavity. The radius of that central cavity is 3.19 cm for the bottom-most three disks and 7.62 cm for the disk immediately below the diaphragm. A vertical slice through the middle of the unmoderated Zeus experiment is shown in Fig. 2 , and a detailed representation of its central region is shown in Fig. 3.

The experimental configuration was slightly supercritical, with a period of approximately 69.5 seconds. This period corresponds to approximately 12.5¢ of excess reactivity and therefore to a value of k_{eff} very slightly greater than 1.0008. The uncertainties associated with the experiment are summarized in Table 1, along with the corresponding calculated uncertainties in reactivity. Several other sources of uncertainty also were investigated but were found to have negligible impact on reactivity and are omitted from the table. The experimental value of k_{eff} for the unmoderated Zeus experiment therefore is 1.0008 ± 0.0015.

Figure 1: Schematic of a Zeus experiment on the Comet vertical assembly machine.

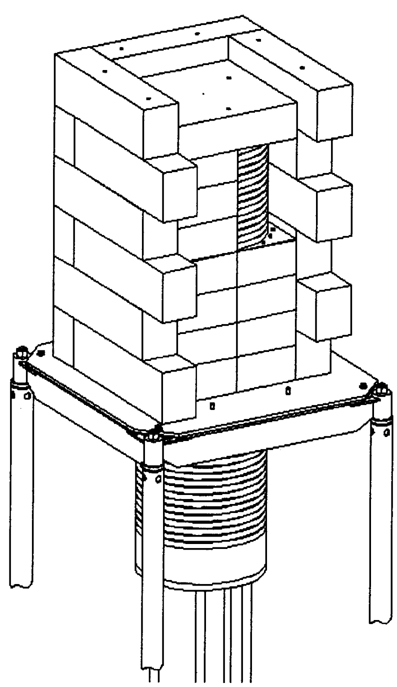


Figure 2: Vertical slice through the center of the unmoderated Zeus assembly.

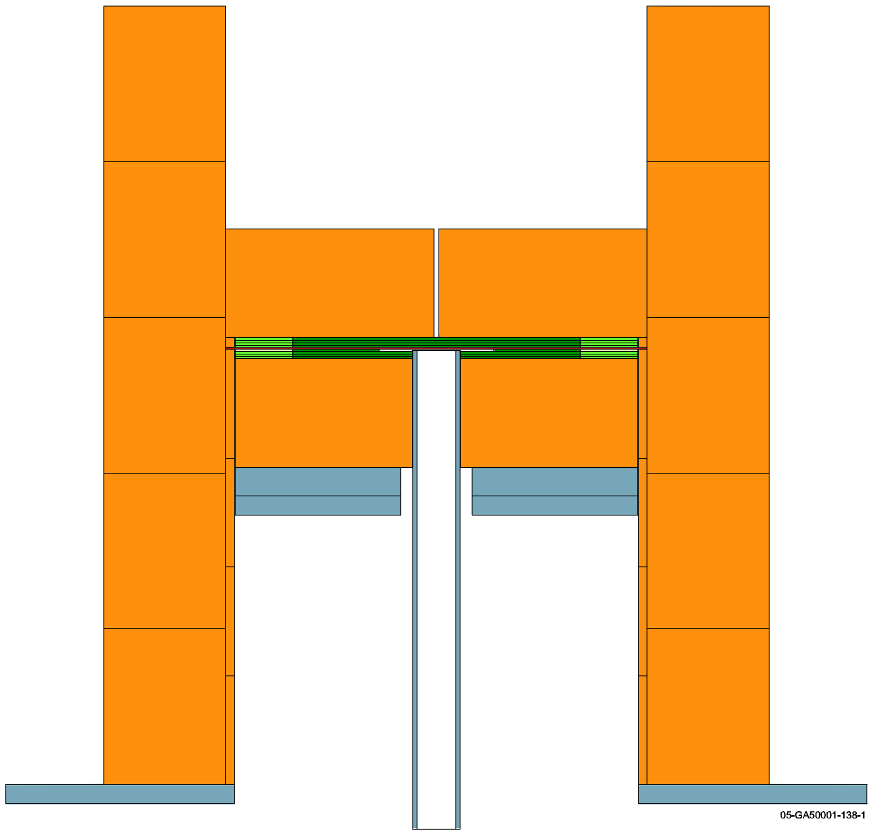
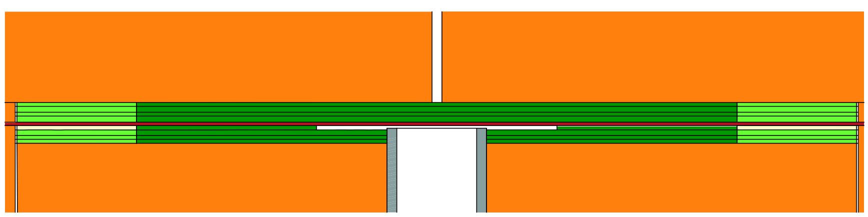


Figure 3: Detail of the central region of the unmoderated Zeus assembly.



3. Analysis of the Experiment

A detailed model of the initial critical configuration was constructed using the MCNP5 Monte Carlo code [5]. The model represents each HEU disk, each HEU annulus, and each part of the reflector individually. In addition, it includes the diaphragm, the alignment tube, the platen and platen adapter plate that attach the lower part of the core to the ram, and the tabletop that supports the upper part of the core.

Four separate calculations were performed with MCNP5. Those calculations employed continuous-energy nuclear-data libraries derived from (1) ENDF/B-V, (2) the final release of

Table 1: Reactivity Impact of Experimental Uncertainties.

Source of Uncertainty	Reactivity Impact (Δk)
Reflector Mass	± 0.0009
Warping of HEU Disks and Rings	± 0.0004
Dimensions of HEU Disks and Rings	± 0.0003
Dimensions of Bottom Reflector	± 0.0004
Dimensions of CR6 Corner Reflectors	± 0.0005
Dimensions of Diaphragm	± 0.0008
Cumulative	± 0.0015

ENDF/B-VI, (3) an ENDF/B-VII pre-release candidate library identified as "β-2", and (4) JENDL-3.3 [6]. The ENDF/B-VI library is a combination of the ACTI [7] and ENDF66 [8] libraries included in the MCNP5 distribution. ENDF/B-VI cross sections also were used in the ENDF/B-VII β-2 calculations for a few isotopes for which ENDF/B-VII cross sections were not readily available (viz., gold and ^{232}U). Each calculation employed 650 generations of 10,000 neutrons each. The first 50 generations were excluded from the statistics, and so each result is based on 6,000,000 active histories.

The results are shown in Table 2. All of the calculated results for k_{eff} differ from the experimental value by three or more standard deviations. However, as Table 3 indicates, the results from JENDL-3.3 and from ENDF/B-VII β-2 improve dramatically when ENDF/B-V cross sections for copper are used. This dramatic change was not observed for previous Zeus configurations, which had intermediate spectra and therefore significantly less neutron leakage. These results suggest that the copper cross sections may be the principal cause of the disagreement between the experimental and calculated values for k_{eff}. Therefore, it is strongly recommended that the fast cross sections for the copper isotopes be reviewed prior to the first formal release of ENDF/B-VII.

Table 2: MCNP5 Results for the Unmoderated Zeus Experiment.

Nuclear Data Library	k_{eff}	Δk
JENDL-3.3	1.0242 ± 0.0003	**0.0234 ± 0.0015**
ENDF/B-V	0.9962 ± 0.0003	**-0.0046 ± 0.0015**
ENDF/B-VI	1.0080 ± 0.0003	**0.0072 ± 0.0015**
ENDF/B-VII β-2	1.0119 ± 0.0003	**0.0111 ± 0.0015**

$|\Delta k| > 3\sigma$

Table 3: MCNP5 Results with ENDF/B-V cross sections for copper.

Nuclear Data Library	k_{eff}	Δk
JENDL-3.3	1.0001 ± 0.0003	-0.0007 ± 0.0015
ENDF/B-VI	0.9968 ± 0.0003	**-0.0040 ± 0.0015**
ENDF/B-VII β-2	1.0007 ± 0.0003	-0.0001 ± 0.0015

2σ <|Δk| < 3σ

4. Benchmark Simplifications

The overall design of the unmoderated Zeus experiment is relatively simple, but the actual configuration is somewhat complicated to model in detail. However, a number of simplifications can be introduced that reduce the complexity but have little overall impact on reactivity. These simplifications can be subdivided into two general categories, geometry and material composition.

The reactivity effect of the simplifications was evaluated using MCNP5 and the ENDF/B-VI nuclear-data library. The calculations for each of the simplifications were performed sequentially, so that each new simplification retained all of the previous ones. With this approach, each result can be compared directly to any previous result, and the statistical uncertainties in reactivity are not compounded.

4.1 Geometry Simplifications

There are three major differences between the ideal benchmark envisioned by the experimenter and the actual critical configurations: the support plate 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, the platen adapter plate, the alignment tube, and the hole in the top reflector that depart from the ideal benchmark but in less important ways. The results from the sensitivity studies that address the geometric modifications to arrive at the benchmark model are summarized in Table 4. These simplifications produce, at most, marginal changes in reactivity, and their cumulative effect is negligible.

In principle, additional simplifications are desirable, but they produce unacceptable changes in reactivity. In particular, removing the diaphragm, eliminating the gap between the top HEU plate and the top reflector, and completely eliminating the alignment tube would have produced reactivity changes of 0.0072 ± 0.0004, 0.0017 ± 0.0004, and -0.0024 ± 0.0004 Δk, respectively. These changes were judged to be too large to accept relative to the simplifications they produce.

4.2 Material Simplifications

A few material simplifications also were made to reduce the complexity of the benchmark model. These simplifications fall into two categories, removing impurities and replacing the densities of individual pieces with the average density for that material. The results from these modifications are shown in Table 5.

In principle, it would be desirable to have a single copper density for the entire reflector and to have a single HEU composition and density. However, such further simplifications produce

Table 4: Reactivity effect of geometry simplifications.

Simplification	Δk	
	Incremental	Cumulative
Convert HEU disks and rings to nominal dimensions	0.0005 ± 0.0004	0.0005 ± 0.0004
Eliminate gap between alignment tube and diaphragm	0.0002 ± 0.0004	0.0007 ± 0.0004
Remove Comet structural support	-0.0002 ± 0.0004	0.0005 ± 0.0004
Eliminate hole in top reflector	-0.0005 ± 0.0004	0.0000 ± 0.0004

Table 5: Reactivity effect of material simplifications.

Simplification	Δk	
	Incremental	Cumulative
Remove impurities from copper	0.0002 ± 0.0004	0.0002 ± 0.0004
Remove impurities from HEU	-0.0008 ± 0.0004	-0.0006 ± 0.0004
Homogenize outer HEU rings and homogenize inner HEU disks (average density and isotopics)	-0.0002 ± 0.0004	-0.0008 ± 0.0004

reactivity changes that are judged to be unacceptable. Specifically, using a single average density for the copper reflector would change reactivity by -0.0029 ± 0.0004 Δk, and using the average density and composition for all of the HEU would change reactivity by -0.0016 ± 0.0004 Δk.

The reflector pieces closest to the HEU core are more dense than those farther away. However, the total mass of those that are farthest away (viz., the side reflectors) is much greater than that of those closest to the core (viz., the top and bottom reflectors). Consequently, a single average density for all of the copper would reduce the reflection produced by the pieces closest to the core and cause an unacceptably large decrease in reactivity.

The situation is similar for the HEU disks and rings. On average, the inner HEU disks have both a higher density and a higher enrichment than the outer HEU rings. Assigning a single average density and enrichment to all of them effectively moves fissile material outward, from a region of higher importance to a region of lower importance, and produces an unacceptably large decrease in reactivity.

4.3 Comparison of Detailed and Benchmark Models

Taken together, the changes in Tables 4 and 5 produce a substantially less complex model of the experiment without altering its basic characteristics. Those simplifications, in conjuction with the experimental value for k_{eff}, produce a value of 1.0007 ± 0.0016 for the benchmark k_{eff}. The impact of the simplifications that produce the benchmark model can be evaluated further by comparing the distributions of the neutrons that cause fission and the number of fission neutrons they produce. Such comparisons, obtained with MCNP5 and ENDF/B-VI nuclear data, are provided in Table 6 and clearly demonstrate the equivalence of the two models. Detailed specifications for the benchmark model are given in the Appendix.

Table 6: Comparison of calculated results from detailed and benchmark models.

Parameter		Model	
		Detailed	Benchmark
k_{eff}		1.0086 ± 0.0003	1.0082 ± 0.0003
Fission Distribution, by Energy	Fast	0.8356	0.8362
	Intermediate	0.1644	0.1638
	Thermal	0.0	0.0
Fission Fraction, by Isotope	^{234}U	0.61	0.61
	^{235}U	98.78	98.78
	^{236}U	0.07	0.07
	^{238}U	0.54	0.54
Average Number of Neutrons Produced per Fission		2.536	2.536

5. Summary and Conclusions

Detailed and benchmark models of the unmoderated Zeus experiment have been created, and it has been demonstrated that the benchmark model retains the reactivity, spectrum, and other important characteristics of the detailed model. In addition, MCNP5 calculations for the detailed model have been performed with four different nuclear-data libraries. All four calculated values for k_{eff} differ from the experimental value by at least three standard deviations. However, JENDL-3.3 and ENDF/B-VII β-2 produce excellent agreement with the experimental value when their cross sections for copper are replaced with ENDF/B-V data. This behavior suggests that the copper cross sections are the principal cause of the disagreement between the reference and calculated values for k_{eff}. Therefore, it is strongly recommended that the fast cross sections for copper be reviewed prior to the first formal release of ENDF/B-VII.

Acknowledgment

Figures 2, 3, A-1, and A-2 were provided by Christine White of the Idaho National Laboratory.

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Appendix
Benchmark Specifications for the Unmoderated Zeus Critical Experiment

Material specifications for the benchmark representation of the unmodified Zeus experiment are shown in Tables A-1 through A-3, and dimensions are given in Table A-4. A vertical slice through the center of the benchmark configuration is presented in Fig. A-1, and a more detailed representation for the central region is shown in Fig A-2.

Table A-1: Isotopic densities for the HEU fuel (atoms/b-cm).

Isotope	Inner HEU Disks	Outer HEU Rings
^{234}U	5.0377×10^{-4}	4.8707×10^{-4}
^{235}U	4.5384×10^{-2}	4.4574×10^{-2}
^{236}U	1.1337×10^{-4}	2.0675×10^{-4}
^{238}U	2.6211×10^{-3}	2.5424×10^{-3}

Table A-2: Copper densities for the reflector pieces (atoms/b-cm).

Top Reflector	Lower Reflector	Inner Reflectors	Outer Reflectors
8.3394×10^{-2}	8.3315×10^{-2}	8.2953×10^{-2}	8.2784×10^{-2}

Table A-3: Elemental densities for the diaphragm, platen, and alignment tube (atoms/b-cm).

Element	Diaphragm	Platen	Alignment Tube
Carbon	2.0673×10^{-4}		
Nitrogen	1.7029×10^{-4}		
Magnesium		6.6049×10^{-4}	6.6049×10^{-4}
Aluminum		5.7816×10^{-2}	5.7816×10^{-2}
Silicon	1.0158×10^{-3}	3.4295×10^{-4}	3.4295×10^{-4}
Phosphorus	4.2278×10^{-5}		
Sulphur	5.8332×10^{-6}		
Titanium		2.5146×10^{-5}	2.5146×10^{-5}
Chromium	1.6442×10^{-2}	7.7185×10^{-5}	7.7185×10^{-5}
Manganese	1.4557×10^{-3}	2.1915×10^{-5}	2.1915×10^{-5}
Iron	5.9554×10^{-2}	1.0061×10^{-4}	1.0061×10^{-4}
Nickel	6.4546×10^{-3}		
Copper	1.5455×10^{-5}	6.9471×10^{-5}	6.9471×10^{-5}
Zinc		3.0687×10^{-5}	3.0687×10^{-5}
Molybdenum	1.3649×10^{-5}		

Table A-4: Dimensions for the core and other cylindrical components.

Component	Top (cm)	Bottom (cm)	Inner Radius (cm)	Outer Radius (cm)
Upper HEU disk (solid)	59.17184	57.97256	—	19.05
Upper HEU ring	59.17184	57.97256	19.05	26.67
Lower HEU disk (wide hole)	57.70880	57.40908	7.62635	19.05
Lower HEU disk (narrow hole)	57.40908	56.50992	3.175	19.05
Lower HUE ring	57.70880	56.50992	19.05	26.67
Lower reflector	56.50992	42.08272	3.175	26.67
Outer reflector	103.25100	0	—	—
Inner reflector	54.24296	0	26.797	—
Upper reflector	73.67016	54.24296	—	—
Platen	42.08272	35.73272	4.7625	26.67
Alignment tube	57.70880	-5.79120	2.54	3.1496

Figure A-1: Vertical slice through the benchmark model.

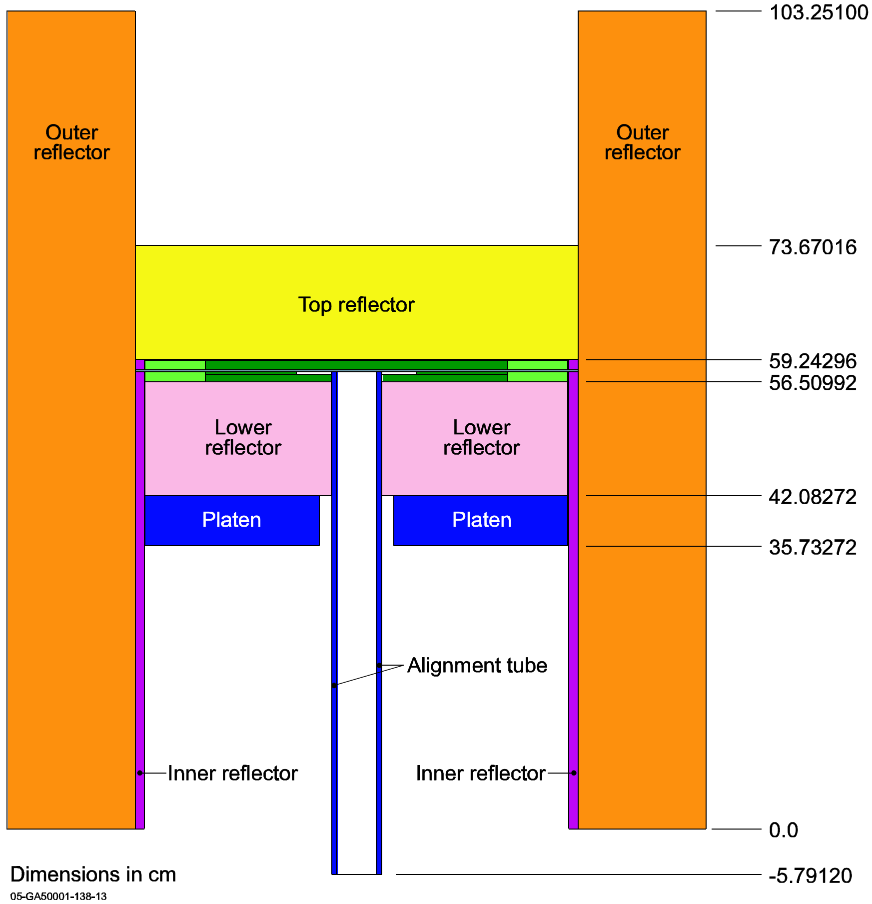

Figure A-2: Vertical slice through the central region of the benchmark model (not to scale).