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Analysis of the First Three Zeus Critical Experiments

Russell D. Mosteller, Roger W. Brewer, and Peter J. Jaegers

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Abstract — The Zeus experiments have been designed to test the adequacy of ^{235}U *cross sections in the intermediate energy range. Detailed models of the three Zeus critical experiments are developed for the MCNP Monte Carlo code, and calculated results, based on cross sections derived from ENDF/B-V and ENDF/B-VI, are presented and assessed. A series of modeling simplifications then is described that transforms the detailed representations into benchmark configurations, and the reactivity impact of each of those simplifications is assessed.*

I. INTRODUCTION

The purpose of the Zeus series of experiments[1,2] is to test the adequacy of the neutron cross-sections of various non-fissile/^{235}U matrices in both intermediate and fast neutron energy spectra. The initial set of experiments was specifically designed to test the adequacy of ^{235}U in the intermediate energy spectrum. This was accomplished by using graphite to reduce the neutron energies to intermediate energy levels.

Intermediate neutron energy spectrum systems have several characteristics that set them apart from either fast or thermal systems. First, intermediate systems are dominated by neutron interactions, e.g. scattering and fission events, which occur at energies ranging from 1 eV to 100 keV. This condition is produced by having a poor moderator in the system; e.g., SiO_2 or iron. Thus, elastic scattering events occur with little energy loss, and neutrons may undergo many collisions before being removed. A second characteristic of intermediate systems is that they typically have a non-fissile/fissile ratio that is in the neighborhood of the maximum on the critical mass curve nearest to the pure metal system. As a result, such systems tend to be physically large.

In designing the Zeus experiment, several factors had to be considered. As mentioned above, intermediate energy systems are large and therefore require a large quantity of fuel. Reflection offers one manner by which the size of the system and hence the required amount of fuel required can be reduced. To this end, a copper reflector was fabricated. Copper was chosen because it is relatively inexpensive, readily machinable, and has the property that neutrons returning to the core have some energy loss but are not overly thermalized. Another consideration in the design of Zeus was the actual fuel itself. Even with the system reflected, a large quantity of fuel is still required. It was determined that a set of highly enriched uranium (HEU) plates called the “Jemima” plates would have more than sufficient mass for the experiment.

II. ZEUS CRITICAL EXPERIMENTS

All three Zeus experiments were constructed on the Comet vertical assembly machine. A cut-away schematic of the Zeus experiments is shown in Fig. 1.

The Zeus cores contained thin, circular platters of HEU separated by thicker platters of graphite. The graphite platters are short cylinders, with an outer radius of 10.5 inches (26.67 cm) and an average thickness of slightly more than 1 cm. The HEU plates also are short cylinders, and, as shown in Fig. 2, they have two components, an inner disk with an outer radius of 7.5 inches (19.05 cm) and a tightly fitting outer ring with an outer radius of 10.5 inches (26.67 cm). The HEU plates are slightly less than 0.3 cm thick. The graphite platters and inner HEU disks in the bottom portion of the cores have a small central cavity with radii of 1.25 inches (3.175 cm) and 1.255 inches (3.1877 cm), respectively, through which an aluminum alignment tube was placed.

The cylindrical core was reflected by copper on the top, bottom, and sides. Inner copper pieces, referred to as corner reflectors, fit closely around the cylindrical core and produced a rectangular exterior surface, as shown in Fig. 3. Heavy copper “logs” then were stacked against the outer sides of the inner copper pieces to form the side reflector. A thick cylindrical piece of copper provided reflection at the bottom of the core, and a square piece of copper rested on top of the corner reflectors, slightly above the topmost graphite platter.

The corner and side reflectors sat on top of the platform of the Comet machine, and a stainless steel diaphragm was inserted part way up the stack of corner reflectors to support the upper portion of the core. The bottom portion of the core rested on the bottom reflector, which in turn was supported by the platen at the top of the machine's vertical drive. Criticality was achieved by driving the bottom portion of the core up inside the reflector until it made contact with the diaphragm.

The same side reflector pieces were used in all three experiments, and most of the corner reflector pieces were the same as well. The differences between the cores of the three experiments are summarized in Table I. The successive decreases in the atom ratio of C:^{235}U, which were achieved by reducing the number of graphite platters in the core, produce an increasingly harder neutron spectrum.

II.A. First Zeus Experiment

The first Zeus experiment achieved initial criticality on April 26, 1999 and contained ten nearly identical "units." For this experiment, a unit consisted of a single HEU platter with four graphite platters above it and four below it. There were four units below the diaphragm, and six units above it, as shown in Fig. 4.

There actually were four distinct, although very similar, types of units. The four units below the diaphragm all had central cavities to accommodate the alignment tube, while the five units above the diaphragm, with one exception, did not. However, the uppermost unit and the unit immediately below the diaphragm were not identical to the other upper and lower units. Although the graphite platters in the uppermost unit were solid, the inner HEU disk in that unit contained the same kind of cavity as the disks below the diaphragm, because only five solid inner disks were available. The unit directly below the diaphragm was modified more extensively. In order to achieve criticality, the two uppermost graphite plates in that unit were replaced with a single graphite platter of half the usual thickness (i.e., approximately 0.5 cm), and a platter of aluminum that was 60 mils (0.1524 cm) thick. This modification was required because, at the time of the experiment, Zeus had an operating limit of 10¢ of excess reactivity.

This configuration actually was very slightly supercritical, with a period of approximately 1100 seconds. This period corresponds to approximately 1¢ of excess reactivity and therefore to a value of k_{eff} between 1.0000 and 1.0001.

Prior to achieving criticality, measurements had been made for two very similar but slightly subcritical configurations. The first subcritical configuration was the most uniform, with units that differed only because of the central cavities in the bottom four units and in the inner HEU disk of the uppermost unit. It is estimated, based on the count rate, that this configuration was approximately 30¢ subcritical. A second attempt at a critical configuration was made by removing the top graphite plate in the unit immediately below the diaphragm . This second configuration was only slightly subcritical, and its count rate was measured for nearly two hours before it could be determined that it was indeed subcritical. The corresponding value for k_{eff} is less than 1.0000 but greater than 0.9999.

II. B. Second Zeus Experiment

The second Zeus experiment achieved initial criticality on October 24, 2000 and contained nine units. For this experiment, a unit contained a central HEU platter with three graphite platters above and three below it. There were two units below the diaphragm and seven units above it, as shown in Fig. 5.

Apart from the central cavities in the two units below the diaphragm, the most significant difference among the units is that the inner HEU disks in the uppermost two units also contain central cavities. HEU disks with cavities were used in those units because only five solid inner disks were available, and the reactivity impact of those two cavities is minimized by placing them in the two units farthest from the center of the core.

This configuration was slightly supercritical, with a period of 170 seconds. That period corresponds to approximately 5¢ of excess reactivity and therefore to a value of k_{eff} very slightly greater than 1.0003.

II. C. Third Zeus Experiment

The third experiment in the series achieved initial criticality exactly one year later than the second, on October 24, 2001. Like the second experiment, it contained nine units. However, for this experiment, a unit contained a central HEU platter with two graphite platters above it and two below it. There were four units below the diaphragm, and five units above it, as shown in Fig. 6.

The most significant difference among the units is that the HEU platter in the bottom unit is simply an inner disk with no outer ring. That unit and the other three units below the diaphragm contain the usual central cavities, while the five units above the diaphragm contain solid HEU and graphite platters.

This configuration was slightly supercritical, with a period of 302 seconds. That period corresponds to approximately 3.7¢ of excess reactivity and therefore to a value of k_{eff} that is very slightly greater than 1.0002.

III. ANALYSIS OF THE EXPERIMENTS

Sensitivity studies were performed to assess the reactivity impact of various experimental uncertainties. In addition, detailed models were developed for each of the three Zeus critical experiments.

III. A. Sensitivity Studies

Three-dimensional calculations with the MCNP4C2 Monte Carlo code[3] were used to determine the sensitivity of the results to the thickness of the graphite plates. The other sensitivity studies were conducted with two-dimensional cylindrical geometries and employed the DANTSYS discrete-ordinates code package[4].

The MCNP4C2 calculations were performed with nuclear data libraries derived from the sixth edition of the Evaluated Nuclear Data File[5] (ENDF/B-VI). Specifically, the MCNP4C2 calculations employed the URES library[6] and, for isotopes not present in URES, the ENDF60 library.[7] The data in the URES library are taken from release 4 (ENDF/B-VI.4), while the data in ENDF60 are taken from release 2 (ENDF/B-VI.2). Each of the MCNP4C2 calculations employed 1,250 generations with 5,000 histories per generation. The first 50 generations were excluded from the statistics, and so the reported results are based on 6,000,000 active histories.

The square outer boundary of the reflector was replaced with a circular boundary that preserved the volume of the reflector for the DANTSYS calculations. All of those calculations were run with S_6 quadrature, P_3 scattering, and a convergence criterion of 10^{-6}. The DANTSYS calculations employed the SCALE 4.3 44-energy-group cross sections,[8] which are derived from the fifth edition of the Evaluated Nuclear Data File (ENDF/B-V).[9]

Results from the sensitivity studies are presented in Tables II and III. As those Tables show, the effects are quite small, with a total uncertainty of ±0.0007 Δk for the first and second experiments and ±0.0008 Δk for the third experiment. The quoted statistical uncertainties in that Table, as well as elsewhere in this paper, are given as single standard deviations (i.e., 1 σ).

What those results do not indicate, however, is the sensitivity of the reactivity to the thickness of the graphite platters. Changing the thickness of the graphite platters does not change the number of mean free paths between adjacent HEU platters, but it does change the surface area on the edges of the platters and therefore the amount of neutron leakage. Changing the thickness of all the graphite platters by their stated tolerance of ±0.005 in., for example, produces reactivity changes of ∓0.0064 Δk, ∓0.0050 Δk, and ∓0.0044 Δk for the first, second, and third experiments, respectively. After the magnitude of this sensitivity was discovered, the thicknesses of subsets of graphite plates were measured very carefully. This measurement established a constraint on the total height of the graphite plates, and that constraint in turn reduces the uncertainty in reactivity by approximately an order of magnitude.

III. B. Detailed Models of the Experiments

In the detailed MCNP4C2 models, each graphite platter was modeled individually, with its own mass and thickness. Similarly, each inner HEU disk and each outer HEU ring were modeled separately, because there were slight differences in density and composition. For example, the enrichment of the individual pieces ranged from 93.15 wt.% to 93.41 wt.%. In addition, the detailed model includes the diaphragm, the alignment tube, each reflector piece, and the platform and platen of the Comet assembly machine.

All of the inner reflector pieces were made from a single block of copper, and the outer copper logs were made from a separate single block. Although the experimenters weighed each copper piece individually, it is reasonable to expect that they are more realistically represented by the average density for all the pieces from that particular block than by the inferred density for each piece. Consequently, only four copper densities were used in the modeling: one for the corner reflectors, another for the side reflectors, a third for the top reflector, and a fourth for the bottom reflector. It is worth noting, however, that the variation in these densities is quite small; the difference between the heaviest and the lightest is only 1.1%.

The MCNP4C2 calculations for the detailed models were performed with nuclear data libraries derived from the fifth and sixth editions of the Evaluated Nuclear Data File (ENDF/B-V and ENDF/B-VI, respectively). The ENDF/B-VI calculations employed the URES library and, for isotopes not present in URES, the ENDF60 library. The data in the URES library are taken from release 4 (ENDF/B-VI.4), while the data in ENDF60 are taken from release 2. Aluminum is the only material present in the Zeus experiments that was updated from release 2 to release 4 but not included in URES. However, its reactivity contribution is quite small, and therefore the ENDF/B-VI results can be considered consistent with ENDF/B-VI.4.

Each of the MCNP4C2 calculations discussed herein employed 1,250 generations with 5,000 histories per generation. The first 50 generations were excluded from the statistics, and so the reported results are based on 6,000,000 active histories.

The calculated values for k_{eff} for the detailed models of the three experiments are shown in Table IV. Both ENDF/B-V and ENDF/B-VI.4 produce an average bias of about

-0.0015 Δk. However, as Table V indicates, the bias from ENDF/B-V is reasonably constant, whereas the ENDF/B-VI.4 bias shows a consistent trend as the spectra of the experiments hardens. This behavior suggests a small energy-dependent bias in the ENDF/B-VI.4 cross sections.

The neutron balances for the three cases are summarized in Table VI. As that Table indicates, ENDF/B-VI.4 produces a smaller capture fraction than ENDF/B-V and a correspondingly larger leakage fraction. The lower capture with ENDF/B-VI.4 is due primarily to copper, although the capture fraction for ^{235}U also is smaller than that with ENDF/B-V.

The average flux and fission spectra within the HEU platters are shown in Figs. 7 and 8. (At the resolution of those figures, the ENDF/B-V and ENDF/B-VI.4 spectra are indistinguishable.) The intermediate-energy range corresponds approximately to lethargy values between 5 and 15. Fig. 8 clearly demonstrates that the Zeus experiments achieve their design objective by producing the great majority of fissions with neutrons in the intermediate energy range.

IV. BENCHMARK SIMPLIFICATIONS

The overall design of the Zeus experiments is relatively simple, but the actual configurations are fairly complicated to model in detail. A number of simplifications can be made that reduce the complexity substantially while having little overall impact on reactivity. These simplifications can be subdivided into two general categories, geometry and material compositions.

The MCNP4C2 calculations for each of the simplifications were performed sequentially, so that with each new simplification the model retained all of the previous ones. With this approach, each result can be compared directly to any previous result, and the uncertainties in reactivity do not compound each other. All of these calculations employed ENDF/B-VI cross sections.

IV. A. Geometry Simplifications

The geometry of the Zeus experiments can be made considerably less complex by removing the diaphragm, removing the platform of the assembly machine, and converting the thicknesses of the graphite plates to a single average value. Further simplifications can be made to remove small void regions. As shown in Table VII, these modifications produce only small changes in k_{eff}.

As Table VII indicates, removal of the void region beneath the top reflector has very little reactivity impact for the first and third experiments. For the second experiment, however, doing so increased reactivity by 0.0025 ± 0.0004 Δk, which was considered too large a change for a single component. Consequently, that void region was retained for the benchmark model of the second experiment but not for the other two.

The possibility of removing the alignment tube and the platen also was investigated. However, their retention does not substantially increase the complexity of the benchmark configuration, and their removal produces reactivity changes of -0.0014 ± 0.0004 to -0.0037 ± 0.0004 Δk, which were deemed too large to accept. The central cavity inside the alignment tube constitutes a streaming path for neutrons, but the tube and the platen partially offset this effect by reflecting some of the neutrons that otherwise would escape from the system.

IV. B. Material Simplifications

The obvious material simplifications are to remove the minor impurities from the various components, replace individual platters by platters of a single, average composition, and to homogenize the copper pieces so that they all have the same density. The reactivity effects of these changes are shown in Table VIII.

The changes to the HEU platters produce more substantial reactivity changes than do those to the graphite platters and the copper reflector. At first thought, it might seem that removing the impurities from the fuel should increase reactivity, because absorbing materials are being removed. However, at these energies, those impurities act more like moderators than absorbers, and therefore their removal can decrease reactivity slightly.

On average, the inner HEU disks have both a higher density and a higher enrichment than the HEU rings that surround them. Specifically, the inner disks have an average density of 18.96 g/cm^3 and an average enrichment of 93.29 wt.%, while the outer rings have an average density of 18.67 g/cm^3 and an average enrichment of 93.17 wt.%. Consequently, the net effect of homogenizing the uranium disks and rings is to move both mass and ^{235}U content outward. Not surprisingly, this movement also can produce a small but statistically significant decrease in reactivity.

IV. C. Summary of Benchmark Simplifications

These simplifications produce cores with platters of uranium and graphite that have uniform densities and isotopic compositions. Consequently, there is no need to retain a distinction between adjacent graphite platters. Similarly, the copper reflector regions all have the same density and composition, and so there is no need to retain the identity of the individual corner and side reflector pieces. Furthermore, the composition of the principal components have been simplified by omitting all impurities.

Specifications for materials in the benchmark models are presented in Tables IX through XII, and the geometry of those models is specified in Tables XIII through XVII. Vertical slices through the center of the benchmark models are presented in Figs. 9,10, and 11.

The process used to establish the value of k_{eff} for the benchmark models is summarized in Table XVIII, and calculated values of k_{eff} for the three models are compared to the benchmark values in Table XIX. Not surprisingly, the biases for these calculated values are very similar to those for the detailed models.

V. SUMMARY AND CONCLUSIONS

The results from the detailed models of the first three Zeus experiments clearly indicate that they achieved the design objective of producing intermediate spectra. Furthermore, those spectra become increasingly harder and the critical mass of HEU becomes smaller as graphite is removed from the core.

The results from the detailed models for the Zeus experiments indicate that both ENDF/B-V and ENDF/B-VI.4 produce values for k_{eff} that agree quite closely with the measured value. They both produce an average bias of about -0.0015 Δk for the three experiments, but the trends are not the same. Specifically, the bias from ENDF/B-V is reasonably constant, whereas the ENDF/B-VI.4 bias shows a consistent upward trend as the spectra of the experiments harden. This behavior suggests a small energy-dependent bias in the ENDF/B-VI.4 cross sections.

ENDF/B-VI.4 produces a smaller capture fraction and a correspondingly larger leakage fraction than ENDF/B-V. This pattern occurs primarily because copper captures fewer neutrons with ENDF/B-VI.4, although the capture fraction for ^{235}U also is smaller than that with ENDF/B-V.

A number of simplifications have been made to transform those detailed models into more straightforward benchmark models. The net reactivity effect of these changes is small, and consequently the reactivity of the benchmark configurations is only slightly different from those of the actual critical configurations.

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LIST OF TABLES

Table I. Summary of the Three Zeus Experiments.

Experiment	HEU Platters*	Graphite Platters	Critical Mass (kg U)	$C:^{235}U$
1st	10	79.5**	125.6	52 : 1
2nd	9	54	112.8	40 : 1
3rd	9	36	106.6	26 : 1

*HEU platters contain both an inner disk and an outer ring, except for the lowermost platter in the third experiment, which was only an inner disk

**Core contained 79 full-height graphite platters, as well as a half-height graphite platter and a very thin stainless-steel platter that acted as a shim

Table II. Reactivity Effects of Mass and Enrichment Uncertainties.

Parameter	Expected Variation (1 σ)	Corresponding Δk	
		1st and 2nd	3rd
Copper Mass	± 0.40 %	± 0.0005	± 0.0006
Graphite Mass	± 0.04 %	± 0.0002	± 0.0001
HEU Mass	± 0.03 %	± 0.0001	± 0.0001
HEU Enrichment	± 0.027 %	negligible	negligible
Cumulative	—	± 0.0005	± 0.0006

Table III. Reactivity Effects of Geometric Uncertainties.

Parameter	Expected Variation (1 σ)	Corresponding Δk
Graphite Platter Thickness	± 0.0086 cm	∓ 0.0005
Graphite Platter Diameter	± 0.0127 cm	negligible
HEU Platter Thickness	± 0.0127 cm	negligible
HEU Platter Diameter	± 0.0241 cm	negligible
Cumulative	—	± 0.0005

Table IV. k_{eff} for Zeus Experiments.

Experiment	Measured k_{eff}	Calculated k_{eff}	
		ENDF/B-V	ENDF/B-VI.4
1st	1.0001 ± 0.0007	0.9989 ± 0.0003	0.9967 ± 0.0003
2nd	1.0003 ± 0.0007	0.9986 ± 0.0003	0.9987 ± 0.0003
3rd	1.0002 ± 0.0008	0.9989 ± 0.0003	1.0006± 0.0003

Table V. Biases for Zeus Experiments.

Experiment	Measured k_{eff}	Δ k_{eff}, Calculated - Measured	
		ENDF/B-V	ENDF/B-VI.4
1st	1.0001 ± 0.0007	-0.0012 ± 0.0008	-0.0034 ± 0.0008
2nd	1.0003 ± 0.0007	-00017 ± 0.0008	-0.0016 ± 0.0008
3rd	1.0002 ± 0.0008	-0.0013 ± 0.0009	0.0004 ± 0.0009

Table VI. Calculated Neutron Balances for the Three Zeus Experiments.

Experiment	Mechanism	ENDF/B-V	ENDF/B-VI.4
	Fission	40.4%	40.4%
1st	Capture	37.6%	34.5%
	Leakage	22.0%	25.1%
	Fission	40.2%	40.3%
2nd	Capture	36.3%	32.9%
	Leakage	23.5%	26.8%
	Fission	40.2%	40.3%
3rd	Capture	34.7%	31.4%
	Leakage	25.1%	28.3%

Table VII. Reactivity Effects of Geometric Simplifications.

Change	Δk		
	1st	2nd	3rd
Convert non-standard unit to standard unit	-0.0022 ± 0.0004	—	—
Same thickness for all graphite plates	-0.0005 ± 0.0004	-0.0001 ± 0.0004	0.0010 ± 0.0004
Change inner radius of HEU disks to 1.25 inches	-0.0001 ± 0.0004	-0.0002 ± 0.0004	-0.0002 ± 0.0004
Remove Comet platform	-0.0007 ± 0.0004	-0.0007 ± 0.0004	-0.0005 ± 0.0004
Remove diaphragm	0.0015 ± 0.0004	0.0011 ± 0.0004	0.0012 ± 0.0004
Fill hole in top HEU platter(s)	0.0004 ± 0.0004	0.0005 ± 0.0004	—
Fill hole in top reflector	0.0002 ± 0.0004	-0.0001 ± 0.0004	0.0003 ± 0.0004
Remove gap above alignment tube	0.0004 ± 0.0004	-0.0003 ± 0.0004	0 ± 0.0004
Remove gap below top reflector	0.0005 ± 0.0004	retained	0.0008 ± 0.0004
Cumulative	-0.0005 ± 0.0004	0.0002 ± 0.0004	0.0026 ± 0.0004

Table VIII. Reactivity Effects of Material Simplifications.

Change	Δk		
	1st	2nd	3rd
Change density of all graphite platters to average	-0.0010 ± 0.0004	-0.0003 ± 0.0004	-0.0004 ± 0.0004
Remove impurities from copper pieces	0 ± 0.0004	0 ± 0.0004	0.0001 ± 0.0004
Change density of all copper pieces to average	-0.0004 ± 0.0004	-0.0005 ± 0.0004	0.0008 ± 0.0004
Remove impurities from fuel	-0.0007 ± 0.0004	0.0003 ± 0.0004	-0.0012 ± 0.0004
Change density and enrichment of all HEU platters to average	0.0003 ± 0.0004	-0.0002 ± 0.0004	-0.0011 ± 0.0004
Cumulative	-0.0018 ± 0.0004	-0.0007 ± 0.0004	-0.0018 ± 0.0004

Table IX. Material Specifications for Reflector.

Material	Density (g/cm^3)	Composition	
		Component	wt.%
Copper	8.7351	Cu	100.000

Table X. Material Specifications for Platen and Alignment Tube.

Material	Density (g/cm^3)	Composition	
		Component	wt.%
Al 6061	2.7000	Mg	1.000
		Al	97.175
		Si	0.600
		Ti	0.075
		Cr	0.250
		Mn	0.075
		Fe	0.350
		Cu	0.275
		Zn	0.125
		Others*	0.075

*Not included in benchmark model

Table XI. Material Specifications for Graphite Platters.

Case	Density (g/cm^3)	Composition	
		Component	wt.%
1^{st}	1.7029	C	100.000
2^{nd}	1.7117	C	100.000
3^{rd}	1.7239	C	100.000

Table XII. Material Specifications for HEU Platters.

Case	Density (g/cm^3)	Composition	
		Component	wt.%
1^{st}	18.804	^{234}U	1.023
		^{235}U	93.234
		^{236}U	0.332
		^{238}U	5.411
2^{nd}	18.816	^{234}U	1.024
		^{235}U	93.224
		^{236}U	0.332
		^{238}U	5.420
3^{rd}	18.809	^{234}U	1.024
		^{235}U	93.237
		^{236}U	0.326
		^{238}U	5.413

Table XIII. Dimensions for HEU / Graphite Units in Benchmark Models.

Case	Region	Bottom (cm)	Top (cm)	Inner Radius (cm)	Outer Radius (cm)
	Upper Graphite	4.32916	8.35860	3.175*	26.670
1st	HEU	4.02944	4.32916	3.175**	26.670
	Lower Graphite	0.0	4.02944	3.175*	26.670
	Upper Graphite	3.32180	6.34388	3.175***	26.670
2nd	HEU	3.02208	3.32180	3.175****	26.670
	Lower Graphite	0.0	3.02208	3.175***	26.670
	Upper Graphite	2.31444	4.32916	3.175*	26.670
3rd	HEU	2.01472	2.31444	3.175*	26.670
	Lower Graphite	0.0	2.01742	3.175*	26.670

*Bottom 4 units only

**Bottom 4 units and top unit only

***Bottom 2 units only

****Bottom 2 units and top 2 units only

Table XIV. Dimensions for Top and Surrounding Reflector Regions in Benchmark Models.

Case	Region	Top (cm)	Bottom (cm)	Inner Radius (cm)	Inner Width, Side-to-Side (cm)	Outer Width, Side-to-Side (cm)
1st	Outer Reflector	123.90120	0	—	55.8800	88.2904
	Inner Reflector	107.86040	9.84720	26.7970	—	55.8800
	Top Reflector	122.28760	107.86040	—	—	55.8800
2nd	Outer Reflector	123.91020	0	—	55.8800	88.2904
	Inner Reflector	102.89540	30.59384	26.7970	—	55.8800
	Top Reflector	117.32260	102.89540	—	—	55.8800
3rd	Outer Reflector	123.90120	0	—	55.8800	88.2904
	Inner Reflector	79.75600	25.96496	26.7970	—	55.8800
	Top Reflector	93.78180	79.75600	—	—	55.8800

Table XV. Dimensions for Central Column in First Benchmark Model.

Region	Bottom (cm)	Top (cm)	Inner Radius (cm)	Outer Radius (cm)
Unit 10	99.50180	107.86040	—	26.6700
Unit 9	91.14320	99.50180		26.6700
Unit 8	82.78460	91.14320	—	26.6700
Unit 7	74.42600	82.78460	—	26.6700
Unit 6	66.06740	74.42600	—	26.6700
Unit 5	57.70880	66.06740	—	26.6700
Unit 4	49.35020	57.70880	3.1750	26.6700
Unit 3	40.99160	49.35020	3.1750	26.6700
Unit 2	32.63300	40.99160	3.1750	26.6700
Unit 1	24.27440	32.63300	3.1750	26.6700
Bottom Reflector	9.84720	24.27440	3.1750	26.6700
Platen	6.03720	9.84720	4.7625	26.6700
Alignment Tube	-5.79120	57.70880	2.5400	3.1496

Table XVI. Dimensions for Central Column in Second Benchmark Model.

Region	Bottom (cm)	Top (cm)	Inner Radius (cm)	Outer Radius (cm)
Unit 9	95.77208	102.11596	—	26.6700
Unit 8	89.42820	95.77208	—	26.6700
Unit 7	83.08432	89.42820	—	26.6700
Unit 6	76.74044	83.08432	—	26.6700
Unit 5	70.39656	76.74044	—	26.6700
Unit 4	64.05268	70.39656	—	26.6700
Unit 3	57.70880	64.05268	—	26.6700
Unit 2	51.36492	57.70880	3.1750	26.6700
Unit 1	45.02104	51.36492	3.1750	26.6700
Bottom Reflector	30.59384	45.02104	3.1750	26.6700
Platen	26.78384	30.59384	4.7625	26.6700
Alignment Tube	-5.79120	57.70880	2.5400	3.1496

Table XVII. Dimensions for Central Column in Third Benchmark Model.

Region	Bottom (cm)	Top (cm)	Inner Radius (cm)	Outer Radius (cm)
Unit 9	75.02544	79.35460	—	26.6700
Unit 8	70.69628	75.02544	—	26.6700
Unit 7	66.36712	70.69628	—	26.6700
Unit 6	62.03796	66.36712	—	26.6700
Unit 5	57.70880	62.03796	—	26.6700
Unit 4	53.37964	57.70880	3.1750	26.6700
Unit 3	49.05048	53.37964	3.1750	26.6700
Unit 2	44.72132	49.05048	3.1750	26.6700
Unit 1	40.39216	44.72132	3.1750	26.6700
Bottom Reflector	25.96496	40.39216	3.1750	26.6700
Platen	22.15496	25.96496	3.1750	26.6700
Alignment Tube	-5.79120	57.70880	2.5400	3.1496

Table XVIII. Determination of k_{eff} for Benchmark Models.

Case	Experimental k_{eff}	Δk due to Benchmark Simplifications	Benchmark k_{eff}
1st	1.0001 ± 0.0007	-0.0023 ± 0.0004	0.9978 ± 0.0008
2nd	1.0003 ± 0.0007	-0.0005 ± 0.0004	0.9998 ± 0.0008
3rd	1.0002 ± 0.0008	0.0008 ± 0.0004	1.0010 ± 0.0009

Table XIX. Results for Benchmark Models.

Case	Benchmark k_{eff}	Library	MCNP4C2 k_{eff}	Δk
1st	0.9978 ± 0.0008	ENDF/B-V	0.9974 ± 0.0003	-0.0004 ± 0.0009
		ENDF/B-VI.4	0.9948 ± 0.0003	-0.0030 ± 0.0009
2nd	0.9998 ± 0.0008	ENDF/B-V	0.9985 ± 0.0003	-0.0013 ± 0.0009
		ENDF/B-VI.4	0.9981 ± 0.0003	-0.0017 ± 0.0009
3rd	1.0010 ± 0.0009	ENDF/B-V	1.0004 ± 0.0003	-0.0006 ± 0.0009
		ENDF/B-VI.4	1.0016 ± 0.0003	0.0006 ± 0.0009

LIST OF FIGURES

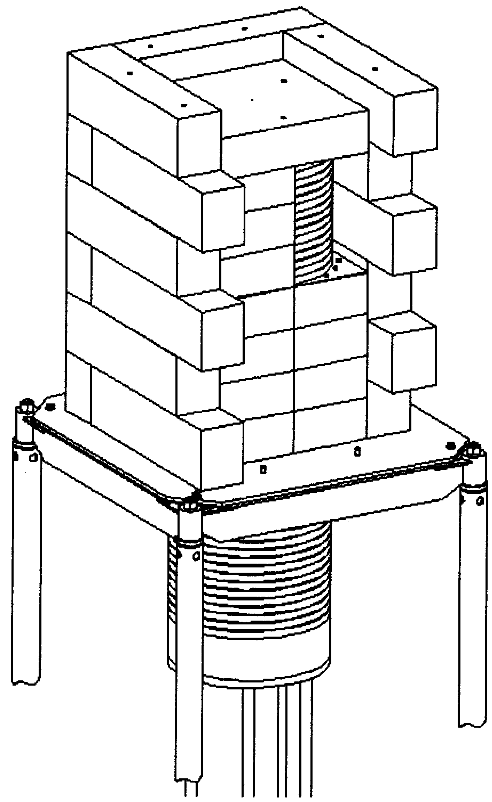


Fig. 1. Schematic of the Zeus Experiments on the Comet Vertical Assembly Machine.

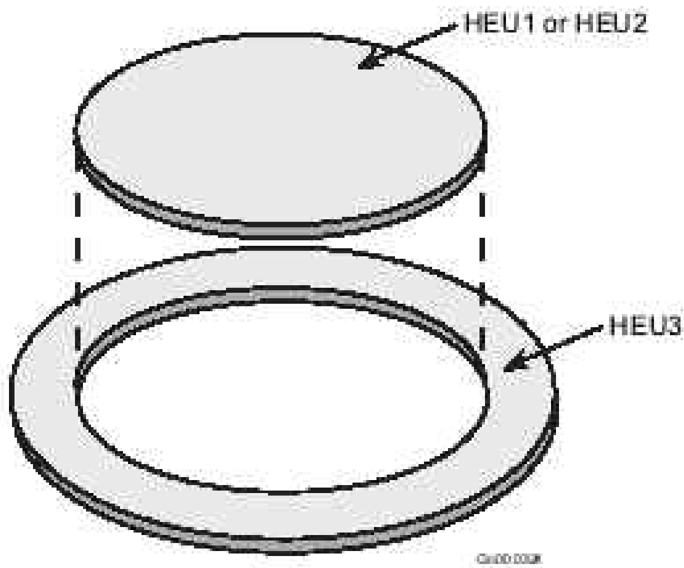


Fig. 2. Structure of Zeus Fuel Platters.

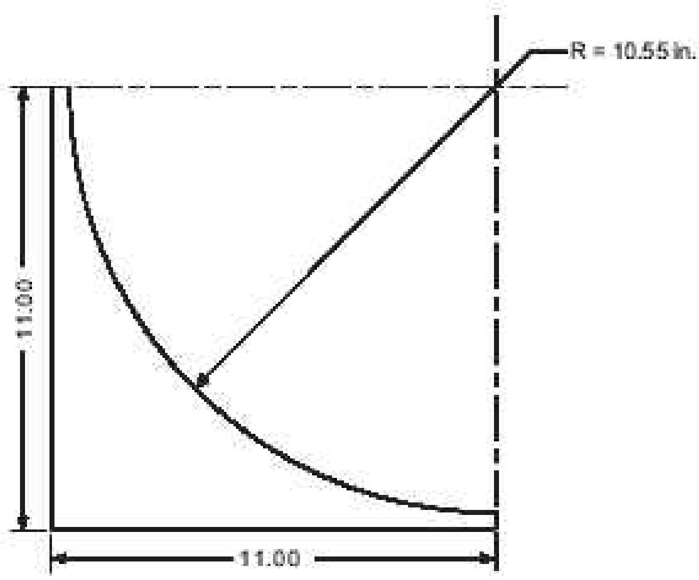
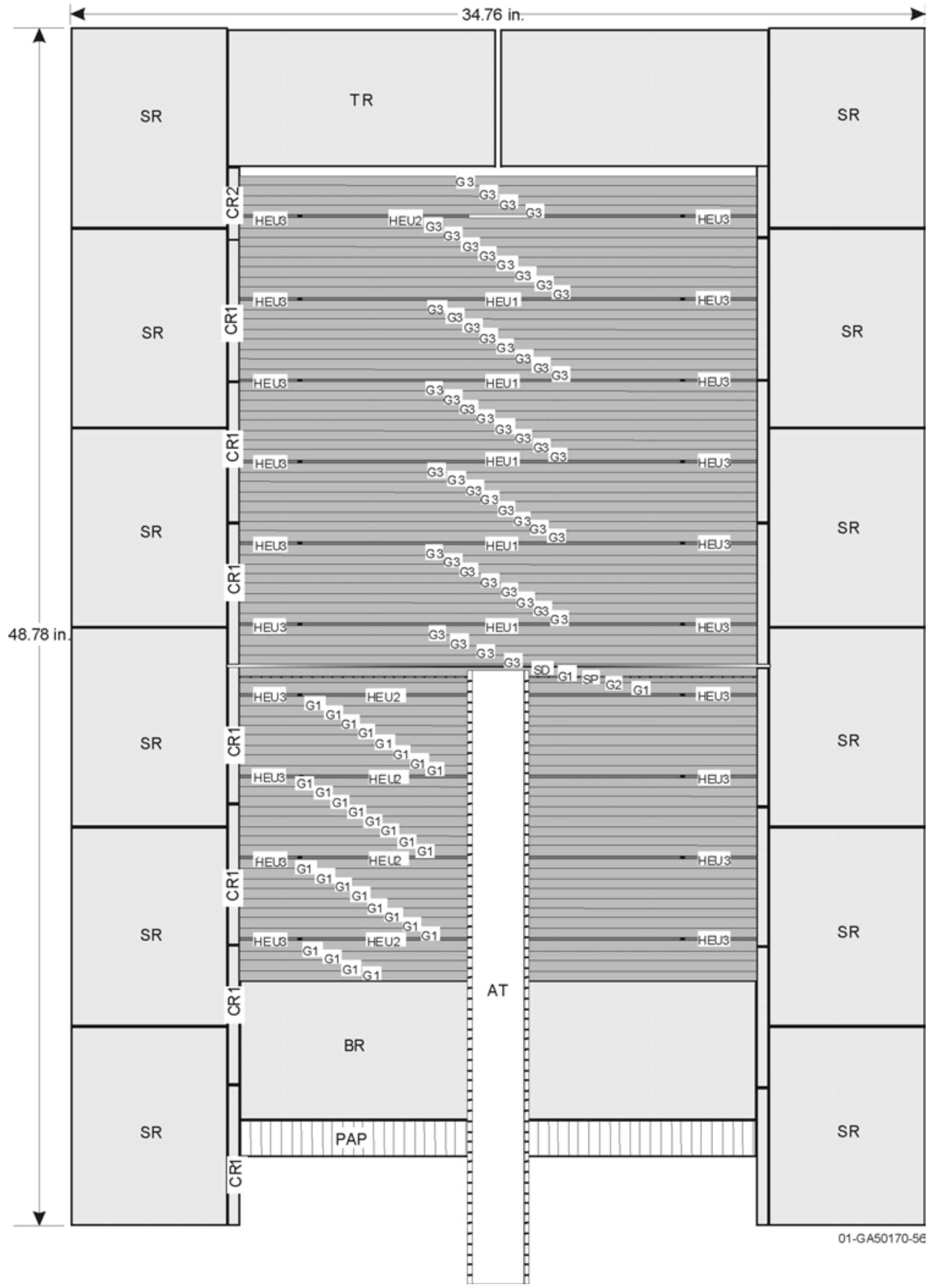
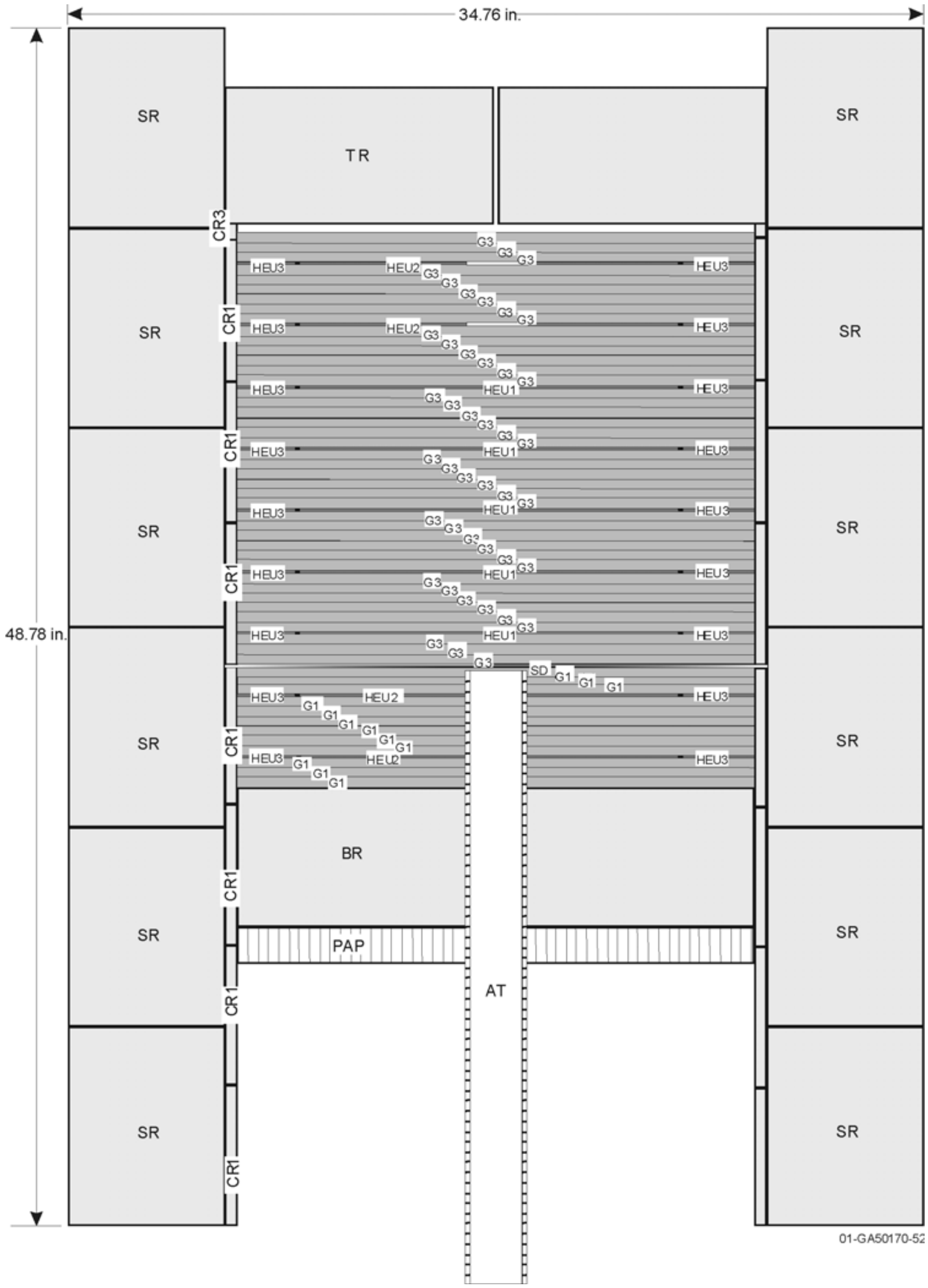


Fig. 3. Structure of Inner Reflectors.



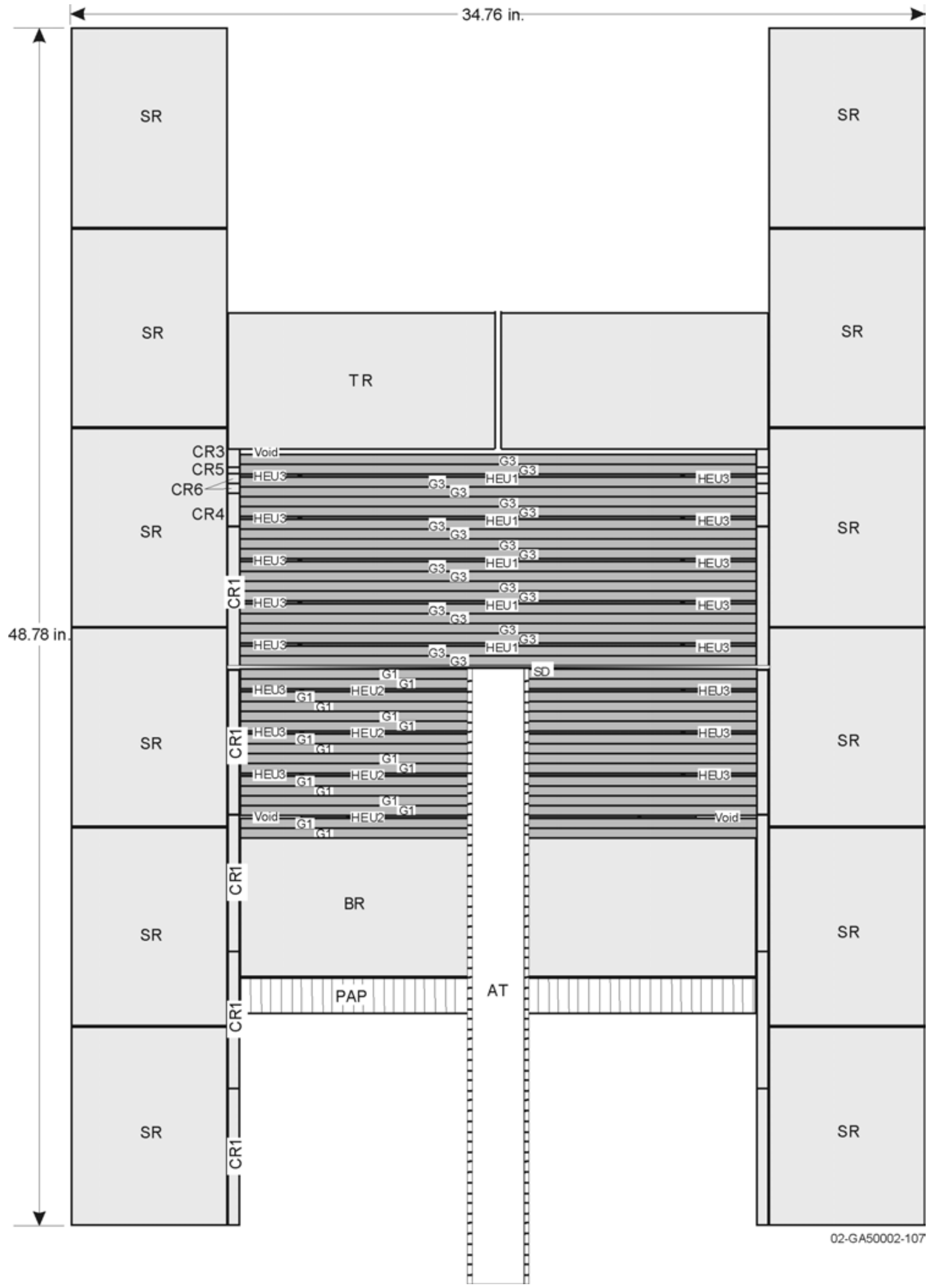
BR	= Bottom Reflector	AT	= Alignment Tube
CR	= Corner Reflector	G	= Graphite Platter
SR	= Side Reflector	HEU	= HEU Platter
TR	= Top Reflector	PAP	= Platen
		SD	= Diaphragm

Fig. 4. Vertical Slice through the First Zeus Assembly.



BR = Bottom Reflector
CR = Corner Reflector
SR = Side Reflector
TR = Top Reflector
AT = Alignment Tube
G = Graphite Platter
HEU = HEU Platter
PAP = Platen
SD = Diaphragm

Fig. 5. Vertical Slice through the Second Zeus Assembly.



BR	= Bottom Reflector	AT	= Alignment Tube
CR	= Corner Reflector	G	= Graphite Platter
SR	= Side Reflector	HEU	= HEU Platter
TR	= Top Reflector	PAP	= Platen
		SD	= Diaphragm

Fig. 6. Vertical Slice through the Third Zeus Assembly.

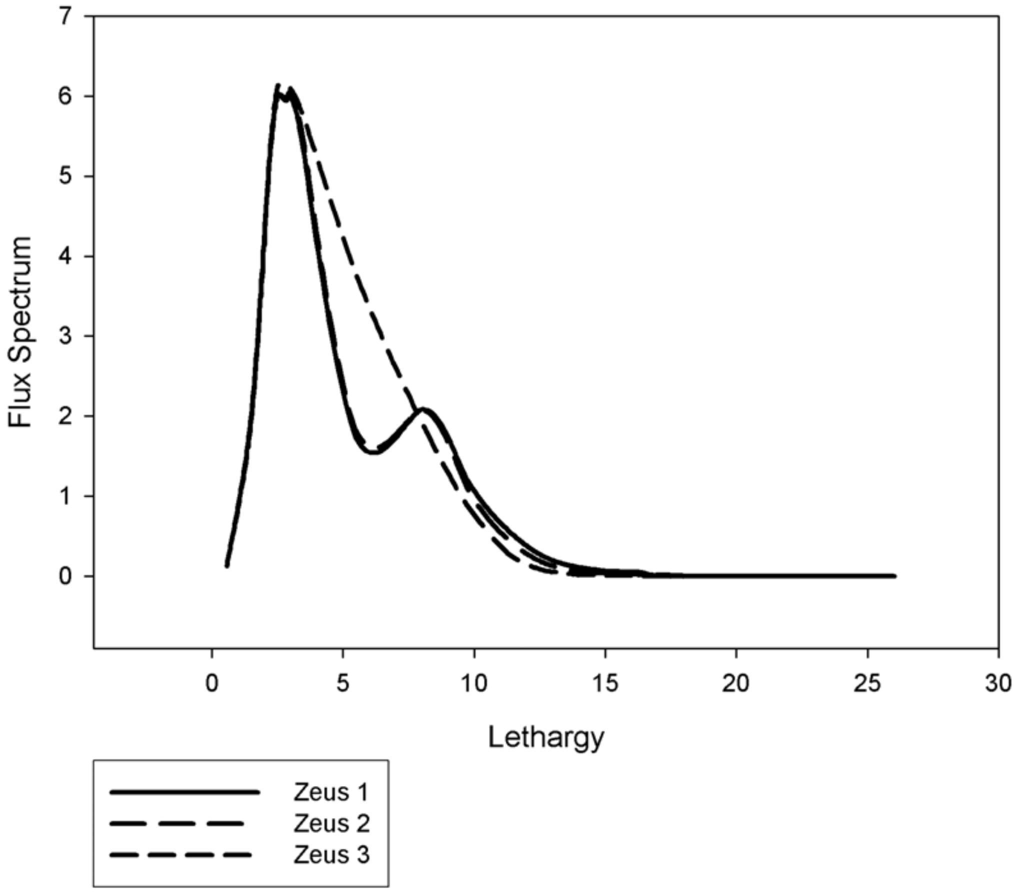


Fig. 7. Flux in Zeus Fuel Platters.

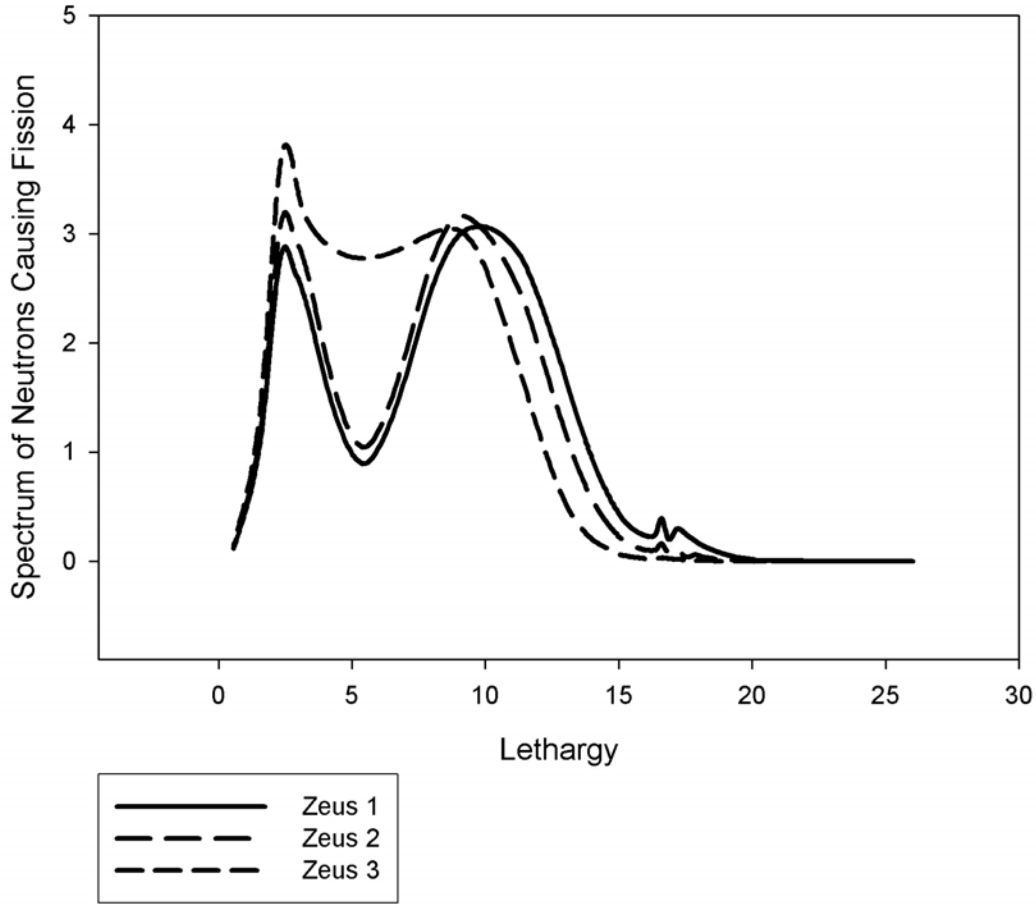


Fig. 8. Spectra of Neutrons Causing Fission in Zeus Fuel Platters.

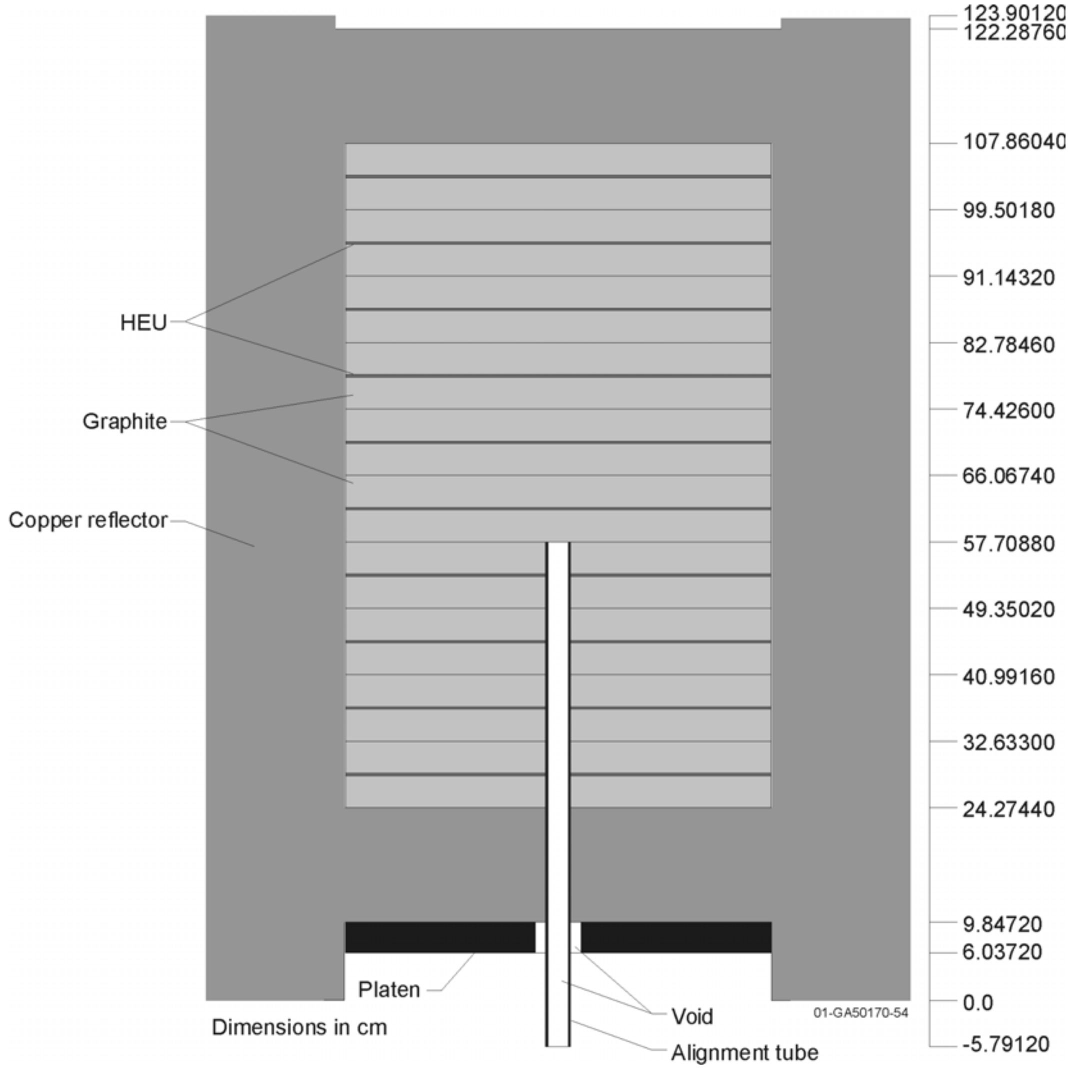


Fig. 9. Vertical Slice through the Benchmark Model of the First Zeus Assembly.

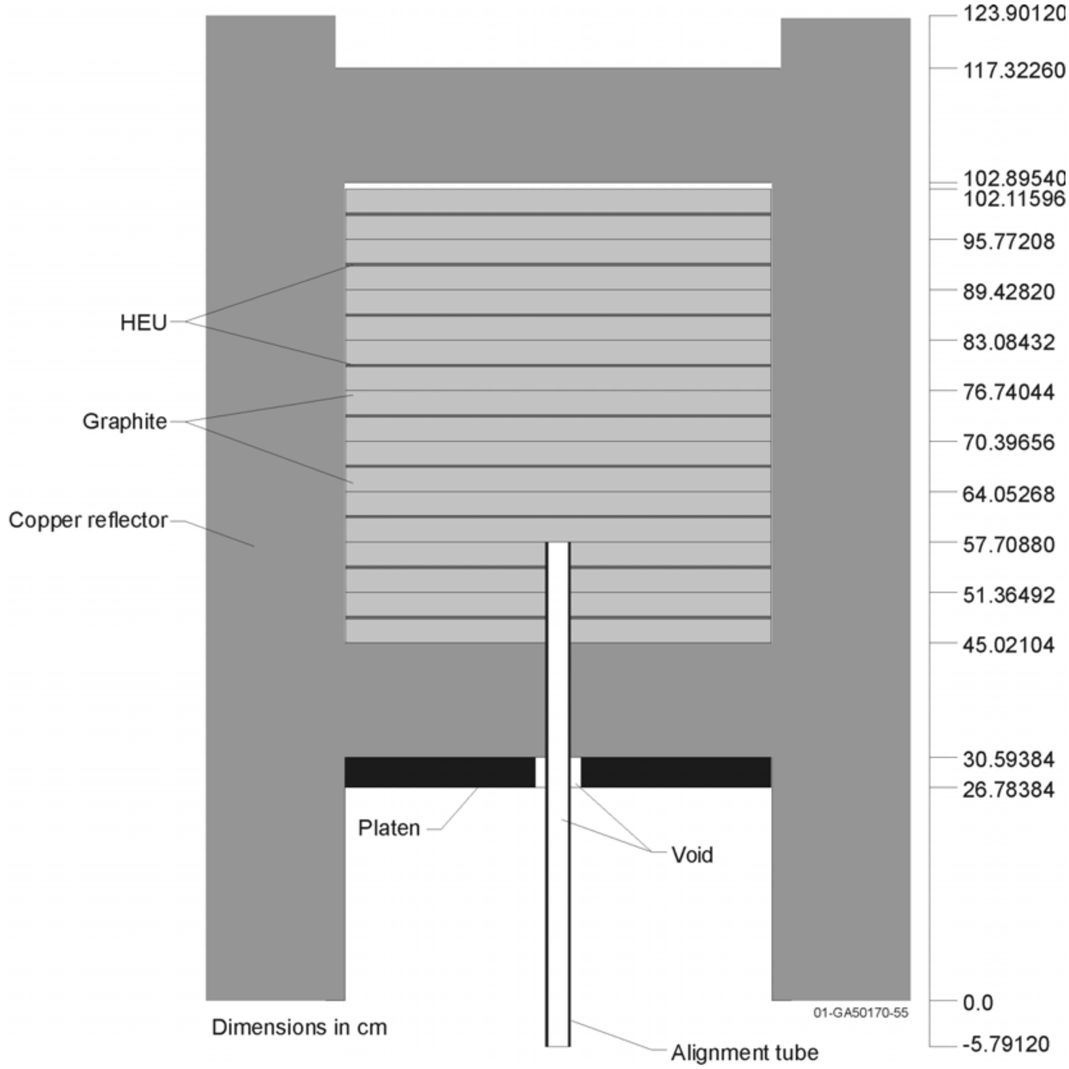


Fig. 10. Vertical Slice through the Benchmark Model of the Second Zeus Assembly.

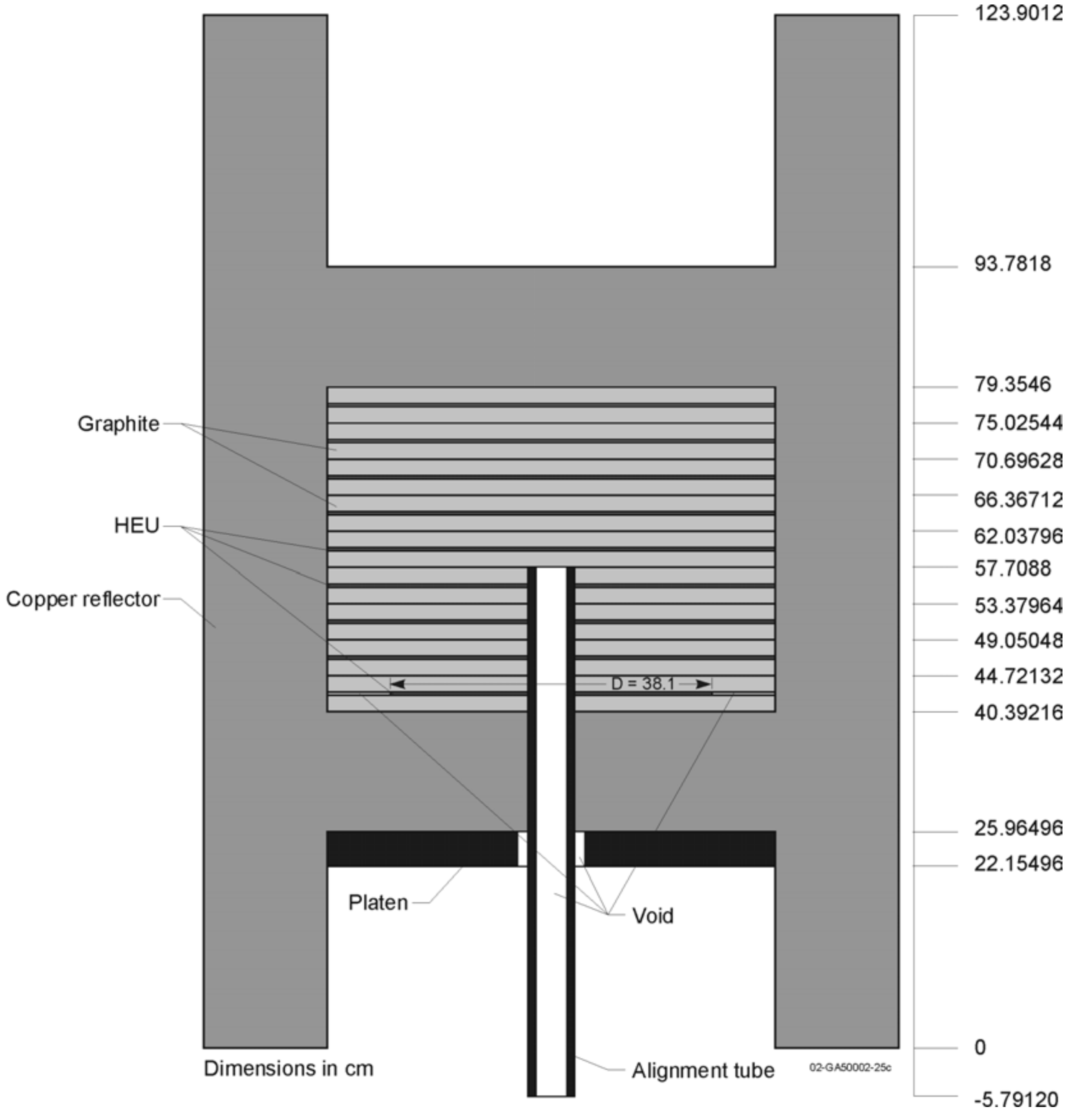


Fig. 11. Vertical Slice through the Benchmark Model of the Third Zeus Assembly.