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Neutronics of the
Phoebus-2 Reactor (U)

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For The Atomic Energy Commission

Bram C. Feldman

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Chief, Reactor, Space and Technology Branch
Division of Classification

UNITED STATES
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**Joseph L. Sapir
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NEUTRONICS OF THE PHOEBUS-2 REACTOR

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Joseph L. Sapir and John D. Orndoff

ABSTRACT

Neutronic studies of the Phoebus-2 rocket propulsion reactor, a prototype for a 5000-MW, 250,000-lb thrust engine, are reported. The neutronic characteristics were established through measurements on a series of critical assembly mockups coupled with a parallel computational program. The full-scale test of this reactor resulted in larger cold-to-hot changes in reactivity than had been predicted. Extensive posttest analysis was able to resolve the discrepancies.

Introduction

By mid-1963 the Los Alamos Scientific Laboratory (LASL) Rover program was well on its way toward establishing the feasibility of uranium-graphite fueled, liquid-hydrogen cooled, solid-core nuclear rocket reactors. It seemed appropriate to begin developing a reactor more suited to the ambitious interplanetary journeys in which nuclear propulsion exhibits its greatest advantage over chemical systems. The reactor program had to be compatible with other technologies (nozzle and pump) and facilities available during a reasonable time schedule. Based upon these considerations, the Space Nuclear Propulsion Office (SNPO) assigned LASL the task of designing, building, and testing a 5000-MW reactor that would serve as the prototype for an engine of approximately 250,000 lb of thrust. This 5000-MW reactor was designated Phoebus. Its specific designation was later changed to Phoebus-2.

The Phoebus Study Group was organized to consider all features of the 5000-MW reactor development and test program. Its recommendations are presented in 16 internal LASL memoranda from which the initial Phoebus-2 reactor specifications emerged. The resulting features affecting the neutronic characteristics of this reactor are discussed below and are compared to those of Kiwi-B4.

Core Size and Composition. Phoebus-2 was designed to operate at an average core power density of twice that obtained in Kiwi. Because the fuel element dimensions

were to remain the same, 2½ times as many fuel elements would be required to produce 5000 MW, resulting in a core diameter of approximately 55 in. vs 35 in. for Kiwi. Uranium-bearing graphite fuel elements with NbC bore coatings were to be utilized. The cluster geometry used in Kiwi, which incorporated one support element for six fuel elements, was to be maintained in Phoebus-2.

Core Void Fraction. A core void fraction of approximately 36% was chosen for Phoebus-2, which corresponded to a reamed flow passage diameter to the fuel of 0.110 in. This hole size was chosen to help alleviate thermal stress and core pressure drop problems that would have been severe with the 0.100-in. hole size used in Kiwi.

Beryllium Reflector. Because of criticality and control considerations, the Phoebus-2 reactor required a reflector thicker than the 4-in. size used in Kiwi. Initial estimates of reflector thickness ranged from 5.5 to 8.0 in. The reflector was to incorporate approximately 18 rotating control drums to provide the required 8 to 10S of control span. Whereas initial plans called for ¹⁰B as the control poison, we substituted natural boron in the form of a boron carbide-copper alloy. This substitution required an increase of the poison plate thickness from the 0.050 in. used in Kiwi to 0.100 in.

Lateral Support Region. Early in the Phoebus-2

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design, structural considerations led to the use of an aluminum cylinder, referred to as an interface cylinder, between the core and reflector to serve the same functions as did the graphite reflector cylinder in previous Rover reactors.

Initial calculations investigating the neutronic feasibility of the Phoebus-2 reactor indicated that uranium loadings and control-rod worths would indeed fall within acceptable ranges. It also appeared that radial fuel loading variation complemented by fuel element flow orificing could adequately flatten the exit gas temperature.

Critical mockup studies were then initiated in the Honeycomb assembly to provide calculational checkpoints and to establish whether the gross features of the design were satisfactory. The Honeycomb measurements did confirm that reactivity and control-rod worth were adequate with reasonable fuel loadings and with ~8-in.-thick beryllium reflector.

The second phase of mockup studies proceeded with construction of a Zepo (zero power) assembly designed to simulate neutronic features in greater detail. Measurements began with a universal beryllium reflector consisting of ~1-in.-thick beryllium annuli so that both inside diameter and thickness could be varied over the range of interest. Mockup fuel elements were extruded in four loading steps with a single central hole equivalent in volume to 19 0.110-in.-diam flow channels. The large central hole allowed insertion of various materials for reactivity coefficient measurements. With combinations of the four loadings, multizoned cores were simulated.

The Phoebus-2 Zepo configuration became progressively more detailed and refined as the design became final. Eventually, the universal beryllium reflector was replaced by a production reflector, and a 90° sector of the core was loaded with actual fuel elements. During this time the ideal situation existed in which the neutronic studies and mechanical design progressed concurrently and complemented each other. As a result, no major neutronic surprises or problems arose during the reactor development.

A calculational effort paralleled the above experimental program. The calculations checked both integral and differential reactivity measurements and guided the design and experiments as changes became necessary. Another important objective of the calculational effort was to predict the reactivity and power distribution during the reactor test. It was in this area that the major neutronic surprises in the Phoebus-2 program appeared. In particular, the observed control-drum positions differed greatly from predicted values whenever the reactor operated at significant power with liquid hydrogen. An extensive posttest analysis, however, was able to resolve these discrepancies and satisfactorily explain the observed reactivity changes.

Throughout the calculational effort, the microscopic cross sections were continually modified and improved. Special attention was given to resonance absorption in nuclides such as uranium, niobium, and tantalum, and to thermalization in graphite, beryllium, and hydrogen.

I. Experimental Program

A. Honeycomb Mockup Measurements

The initial Phoebus-2 critical experiments were performed on the Honeycomb assembly machine. This machine (Fig. 1.1) consists of two stacks of aluminum tubes that are 3-in. square by 36-in. long with a 0.047-in. wall. The two stacks may be brought together by remote control to form a 6-ft cubic matrix of tubes. Critical assemblies are built up by slipping fuel and reflector materials, usually in the form of foils and slats, into the aluminum tubes.

The initial Honeycomb assembly was an enriched uranium-graphite core surrounded laterally by a thin graphite cylinder and a beryllium reflector. Niobium concentration was increased in steps from zero to the equivalent of 110 g/fuel element with compensating increase of uranium. Thus, calculational checkpoints were provided for the effect of niobium in a wide range of neutron spectra. Following this survey, attention was concentrated on mocking up specific Phoebus-2 configurations. An early modification was the replacement of the graphite cylinder with an aluminum one. The radial fission density was flattened by using three fuel loading zones.

Additional subdivision of the core did not seem warranted because of the gross nature of the graphite plate-uranium foil fuel mockup. Core reactivity coefficients were measured for materials of interest to be used as calculational checks and to extrapolate reactor design modifications. Control-rod simulation experiments were performed to predict total drum span. Although the simulations were geometrically crude, predictions based on these measurements were remarkably accurate.

The Honeycomb experiments early confirmed that satisfactory neutronic characteristics of Phoebus-2 were attainable. The experiments are discussed in further detail in the following sections and the corresponding calculations are discussed in Sec. II.A.1.

1. Honeycomb Mockups to Check Niobium Cross Sections. In the process of building up to the final Honeycomb assembly, a deliberate effort was made to obtain critical data at various concentrations of niobium. The motive was to provide a computational test set to check the validity of available niobium cross sections. Because of the large amount of reactivity associated with niobium, it was important that its cross section be established. At

Fig. 1.1
Honeycomb assembly with Phoebus mockup.

that time it was felt that uncertainty in niobium was the greatest deficiency in Phoebus computations.

Figure 1.2 shows schematically the attempt to mock up the cylindrical Phoebus-2 geometry in the rectangular 3 in. by 3 in. Honeycomb structure. At this stage of the Phoebus design, a graphite reflector cylinder was being considered for the transition region between core and reflector. The core volume was loaded with graphite slats to produce a distributed void fraction of about 30%. In all cases the mockup was uniform along its 52-in. length and unreflected at both ends. Criticality was attained by adding 0.002-in.-thick foils of U(93) uniformly throughout the core volume.

Niobium effectiveness was measured in six assemblies with $C/^{235}\text{U}$ atomic ratios varying from 280 to 1450 and consequently in a wide range of neutron flux spectra. The niobium was added in the form of 0.005-in. foils, uniformly distributed. During these experiments, the dimensions were maintained constant with only niobium and uranium densities in the core being varied. The resulting compositions of the six assemblies are summarized in Table 1.1. Figure 1.3 shows the relationship between critical mass and niobium loading. Core-average reactivity coefficients are given by Fig. 1.4 as a function of the niobium content, and radial variations of these coefficients appear in Fig. 1.5 through 1.7. The worth of

Fig. 1.2.
Cross section of simplified Phoebus mockup in Honeycomb.

beryllium for various radii within the reflector is shown in Fig. 1.8 for two niobium loadings.

2. Honeycomb Mockups of Phoebus-2. In the second phase of the Honeycomb work, the assembly was modified to more closely approximate the then current Phoebus-2 design. A major change in the configuration was the substitution of an aluminum interface cylinder for the graphite one in the previous assemblies. The uranium loading remained uniformly distributed throughout the core. A schematic of the new mockup is shown in Fig. 1.9. The dimensions and compositions are summarized in Table 1.2 along with some measured values of core-average reactivity coefficients. Correction of the actual uranium mass for the presence of the aluminum in the Honeycomb matrix resulted in a predicted Phoebus-2 critical mass of 294 kg. It may be noted that four years later the Phoebus-2 reactor went critical at the Nuclear Rocket Development Station (NRDS) in Nevada with a uranium inventory of 297 kg.

The next modification was to redistribute the uranium into three radial zones in an initial step toward flattening the radial power distribution. Table 1.3 presents a summary of the material densities and weights. The critical mass increased by only 4 kg to a value of 264 kg (or 298 kg corrected for the aluminum). Figure 1.10 shows the relative fission densities as a function of radius for the uniform and zoned cores. The fissions/gram at the

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TABLE I.1
PHOEBUS HONEYCOMB, DIMENSIONS AND COMPOSITIONS FOR CRITICALITY

<u>Region</u>	<u>Radii, in.</u>	<u>Material</u>	<u>Weight, kg</u>	<u>Homogenized Density, g/cm³</u>	<u>Atomic C to U²³⁵ Ratio</u>
Reflector	27.5 to 29.5	Graphite	441.1	1.45	
Reflector	29.5 to 36.0	Beryllium	1905.9	1.67	
Honeycomb matrix	72-in. cube	Aluminum		0.165	
Core	0 to 27.5	Graphite	2369.4	1.17	
	<u>Assembly Number</u>				
	1	Niobium U(93)	0 34.4	0 0.0170	1450
	2	Niobium U(93)	27.8 38.2	0.0137 0.0189	1300
	3	Niobium U(93)	54.7 42.3	0.0270 0.0209	1180
	4	Niobium U(93)	109.7 53.5	0.0542 0.0264	932
	5	Niobium U(93)	219.8 89.7	0.1086 0.0443	629
	6	Niobium U(93)	444.6 189.3	0.220 0.0935	279

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Fig. 1.3.

Variation of critical mass with niobium loading.

Fig. 1.5.

Radial dependence of uranium reactivity for various Honeycomb assemblies.

Fig. 1.4.

Variation of uranium, carbon, and niobium reactivity with core niobium loading.

Fig. 1.6.

Radial dependence of niobium reactivity for various Honeycomb assemblies.

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Fig. 1.7.

Radial dependence of graphite reactivity for various Honeycomb assemblies.

Fig. 1.8.

Radial dependence of reflector beryllium reactivity.

core edge relative to the center is not as peaked in these mockups as in Kiwi-B4 even though no control poison was present in the Honeycomb reflector. However, because the Honeycomb distribution dips to lower values than did the Kiwi, the overall maximum-to-minimum fission ratio is comparable in the two reactors. Measured reactivity coefficients for uranium, niobium, tantalum, carbon, and hydrogen as functions of radius are shown in Figs. 1.11 through 1.13 and axial variations of carbon and hydrogen coefficients in Fig. 1.14.

Fig. 1.9.

Cross section of Honeycomb mockup of Phoebus-2.

The first information for estimating control-rod effectiveness was obtained in Honeycomb by measuring the reactivity of a 0.050-in. boral (20 wt% ^{10}B , 8 wt% Al) plate as a function of radial position in the reflector. The resulting distribution function, shown in the upper portion of Fig. 1.15 was integrated over a control vane at a series of angular settings to obtain the ideal, isolated control-rod response curves shown in the lower portion of the figure. The estimated span of a single 120° drum is shown to be 57¢ resulting in a total control span of 10.25\$ for 18 drums. It was expected, however, that in the actual reactor interaction between drums would reduce this total span.

B. Phoebus-2 Zepo: Core Design I

After the initial Honeycomb work, the Phoebus-2 Zepo assembly machine was used for more detailed mockups of the Phoebus design. The Zepo machine was kept current by continuous modification from its inception to the final fine-structure fission measurements. An overall view of the Zepo assembly is shown in Fig. 1.16. The assembly was designed to provide flexibility in both the core and the reflector.

The core was contained in an aluminum can that simulated neutronically the interface cylinder used in the reactor design. For critical measurements, the core was inserted into the reflector remotely by a hydraulic lift. For accessibility the core could be rolled from beneath the reflector into an open area.

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TABLE I.2

HONEYCOMB-PHOEBUS-2

Composition of Uniform Core Loading

Region ^a	Outer Radius, in.	Volume, liters	Material	Weight, kg	Homogenized Density, g/cm ³
Core	27.50	2025	Carbon	2369	1.170
			Uranium(93)	260 ^b	0.1284
			Niobium	361	0.1783
			Aluminum	334	0.165
Interface	30.65	490	Aluminum	795	1.621
Reflector	38.15	1381	Beryllium	2311	1.673
			Aluminum	228	0.165

^a52-in.-long core and reflector.

^bRemoval of the matrix aluminum increases the critical mass from 260 to 294 kg.

Core Average Reactivities of Various Materials

Material	Worth, ρ /kg	Type of Sample
Uranium(93)	+ 7.34	0.002-in. foil
Graphite	+ 3.0	0.28-in. slats
Aluminum	+ 0.73	1/16-in. sheet
Inconel	- 0.7	1/8-in. wire
Niobium	- 2.55	0.005-in. foil
Hydrogen	+ 470.	1/16-in. polyethylene

TABLE I.3

HONEYCOMB-PHOEBUS-2 COMPOSITION
(Three-Zone Core)

Region ^a	Outer Radius, in.	Homogenized Density, g/cm ³				
		Al	Be	C	Nb	U
Fuel	14.75	0.165		1.1783	0.1783	0.121
	24.88	0.165		1.170	0.1783	0.1540
	27.50	0.165		1.170	0.1783	0.0770
Can	30.65	1.620				
Reflector	38.15	0.165	1.674			
Total weights, kg:		1357	2312	2369	11 ^b	264

^a52-in.-long core and reflector.

^bCorresponds to ~90 g/fuel element.

Fig. 1.10.
Fission density and relative loading vs radius for the uniform and the zoned Phoebus mockup.

Fig. 1.12.
Radial dependence of niobium and tantalum reactivity for the zoned Honeycomb Phoebus mockup.

Fig. 1.11.
Radial dependence of U(93) reactivity for the uniform and zoned Honeycomb Phoebus mockup.

Fig. 1.13.
Radial dependence of carbon and hydrogen reactivity for the zoned Honeycomb Phoebus mockup.

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Fig. 1.14.

Axial Variation of graphite and hydrogen reactivity.

Fig. 1.15.

Incremental reactivity of 0.050 in. borol (20 w% B¹⁰) and deduced integral control-rod worth.

The Zepo fuel elements were extruded hexagonal prisms, 52 in. long, with a single 0.48-in.-diam central hole representing the 19 0.110-in.-diam flow channels in the production elements. For economy, the elements were not machined so that the fit-up in the core was not as precise as with production elements. Four loading steps of 100, 200, 300, and 400 mg/cm³ were available for tailoring the radial fission distribution. Niobium tubes in two sizes, weighing 25 and 75 g, were available for insertion into the central hole to simulate the bore coatings expected in the reactor. By various combinations of these tubes, coatings of 25, 75, or 100 g/element could be mocked up and reactivity as a function of niobium content could be checked. Initial mock-up support elements were graphite hexes with a 0.50-in.-diam central hole. Graphite rods, 25 in. in diam, were inserted into the central holes to simulate the pyrolytic graphite liners present in the reactor. Later, support elements were fabricated with smaller holes to include the graphite equivalent of the pyrolytic graphite liners and to eliminate the need for the filler rods, thus enabling the inclusion of Inconel tubes inside the central hole to represent the reactor tie tubes.

At a late stage in the Phoebus-2 Zepo program, a 90° sector of the core was loaded with 19-hole fuel elements and production-type support elements. Detailed fission mapping was carried out in this sector.

A universal beryllium reflector consisting of concentric 7/8-in.-thick beryllium annuli was used in the initial Zepo measurements. With the available pieces the inside diameter and thickness could be varied over the range of interest. Figure 1.17 shows a 7-in.-thick reflector from the top with the core lowered. The pattern of fuel elements seen in the lower portion of the figure is the result of painting the ends of the elements different colors so as to recognize easily the different loadings. Note the 12-sided core periphery. The blade-type control elements shown in Fig. 1.17 are stainless-steel-clad cadmium plates inserted into a 1/8-in. gap between the beryllium annuli. Two of these served as control rods and four served as safety rods. These rods controlled the Zepo assembly and were not meant to represent the rotating drum system planned for the actual reactor. Later in the program, a production reflector incorporating the actual control drums was substituted for the universal reflector.

1. Initial Critical Conditions. The first Zepo stacking was a three-zone core modeled after the final Honeycomb configuration. There was no attempt in this case to differentiate between fuel-element and support-element locations. The elements were combined to give the desired

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Fig. 1.16.
Phoebus-2 Zepo assembly.

homogeneous loading in each of the three zones. The distribution of fuel elements in a 60° sector is shown schematically in Fig. 1.18. The average composition of the five types of elements is given in Table I.4, and dimensions and composition of the assembly appear in Table I.5. The resulting excess reactivity of this reactor configuration was 2.6\$. The critical condition in Honeycomb and Zepo are compared in Table I.6 by using reactivity coefficients measured in Honeycomb. This crude comparison predicts the Zepo reactivity to within 1\$.

Fig. 1.17.
Phoebus-2 Zepo universal reflector.

2. Control Measurements. Control-rod effectiveness (as well as reactivity and fission distribution) was a primary concern in the Phoebus-2 design. Although preliminary calculations and crude Honeycomb measurements had produced initial estimates of control-rod worth, it was essential to obtain confirmation from a realistic critical mockup. The two main problem areas were in simulating the rotating vane geometry of the proposed control rods and in determining the amount of interaction between adjacent rods. Both an 18-rod and a 24-rod system were considered in a beryllium reflector ranging from 7 to 8 in. thick. The resulting estimated control span for 18 rods in an 8-in. reflector was 7 to 8\$. The span was very sensitive to the presence of absorbing materials in the reflector and interface regions.

TABLE I.4
PHOEBUS-ZEPO ELEMENT COMPOSITION

Type	0	01	02	03	04
Nominal loading, mg/cm ³	0	100.	200.	300.	400.
Average uranium weight, g	0	27.07	53.99	79.50	105.5
Average carbon weight, g	470.3	492.9	489.8	464.9	460.3

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Fig. 1.18.
Phoebus-2 Zepo initial stacking.

Initial control measurements in Zepo were with eight 7/8-in.-thick beryllium annuli nominally spaced 1/8 in. apart. Control vane material was 0.050 in., fully enriched boral, identical to that used in Kiwi reactors. Figure 1.19 shows the reactivity worth of a single boral vane positioned in the innermost reflector gap as a function of the circumferential vane width. The curve extrapolates to a value of 16.1\$ for a complete curtain.

Interaction, or shadowing effects, between control rods became apparent from measurements with a succession of equally spaced boral strips representing either 18 or 24 control rods. It was found that the reactivity contribution per strip became constant after the first two strips had been added, indicating that interaction was principally between adjacent strips. Consequently, the average interaction between elements of a series may be characterized by the ratio of effectiveness of the third element to that of the first (isolated case). The shadowing effect plotted in Fig. 1.20 is seen to be more pronounced the wider the vanes and the closer the separation. For these and subsequent experiments, half-length control elements were measured and then scaled to full length. The dependence upon length of control strip inserted is given in the differential curve of Fig. 1.21. A more detailed control-rod mockup consisted of three boral elements positioned as shown in Fig. 1.22 where control angles at 0 and 180° are represented by the solid and dotted lines,

respectively. Resulting 0 to 180° span values in 8-in.-thick beryllium (at 12.5% void) are 9.3 and 10.8\$ for 18 and 24 rods, respectively.

Removal of the outermost 7/8-in.-thick annulus of beryllium reflector gave a 1.4\$ loss in reactivity with an unpoisoned reflector, but resulted in a more drastic loss of 2.4\$ in control span for the 24-rod geometry. Various design concepts for springs and control vane cans utilized titanium, Inconel, or stainless steel in the reflector or interface region. Although these materials are relatively modest neutron absorbers, their use seriously reduced the measured control span. Figure 1.23 demonstrates the effect upon boral reactivity by reducing reflector thickness and introducing titanium torsion tubes. Inconel sheet had the same reactivity contribution whether inside or outside the aluminum can, indicating that the effectiveness of structural materials in the interface region is insensitive to exact location. The summary of experiments in Table 1.7 shows how control range is influenced by various design features. As a result of these measurements, titanium, Inconel, and stainless steel were eliminated in the interface region and replaced with aluminum wherever possible.

During the design of Phoebus-2, it was decided to use natural boron in the form of a boron carbide-copper alloy as the control plate material instead of the fully enriched boral in the Kiwi and Phoebus-1 reactors. Test plates of B₄C-Cu, 2 by 13 by 0.05 in., were fabricated by LASL Group CMB-6 with 20, 40, and 50 vol % B₄C. Reactivity contributions of these plates in the innermost reflector annulus were measured and compared with that of a Kiwi boral plate of the same size. The B₄C-Cu plates were used in single, double, and triple thickness to provide a wide range of points. The results shown in Fig. 1.24 indicate that the effectiveness is a function of the surface density of ¹⁰B alone. The proposed boron-copper material was identical to the boral at the same concentration of ¹⁰B. The matrix material and ¹¹B content appeared to have no influence upon the control worth. The solid curve in Fig. 1.24 is a fit obtained with a two-term saturation function

$$Y = a_1 (1 - e^{-b_1 x}) + a_2 (1 - e^{-b_2 x})$$

in which

$$a_1 = 0.612$$

$$b_1 = 274$$

$$a_2 = 0.495$$

$$b_2 = 25.5$$

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TABLE 1.5
PHOEBUS-ZEPO COMPOSITION

Region	Outer Radius, in.	52-in.-long Core and Reflector					
		Homogenized Density, g/cm ³					
		Al	Be	C	Nb	U	Fe
Fuel	14.814			1.130	0.1497	0.1329	
	24.886			1.111	0.1476	0.1716	
	27.416			1.142	0.1432	0.0908	
Core edge	27.843			1.684			
Can	31.063	1.546					
Reflector	39.500		1.515				
Total weights, kg:		785.1	2414	2364	296.7	293.4	

30.578-in. Radius Inlet Materials

Region	Axial Station, in.		
	0		
Plate		2.710	
	-0.5		
Picnum			0.3177
	-3.5		
Block		2.710	
	-9.5		
Total weights, kg:		849.0	53.52

TABLE 1.6
HONEYCOMB-ZEPO REACTIVITY COMPARISON

Material	Honeycomb	Zepo	kg Δm	c/kg	Δk S
Carbon	2369	2364	- 5	3.05	-0.15
Niobium	361	296	- 65	- 2.52	1.64
Uranium	264	293	29	7.18	2.08
Aluminum (core)	334		- 334	0.73	- 2.44
Aluminum (reflector cyl.)	794	785	- 9	0.4	- 0.04
Aluminum (end)		849	849	0.22	1.87
Aluminum reflector	228		- 228	0.2	- 0.46
Beryllium	2311	2414	103	0.80	0.82
Zepo excess reactivity estimated from Honeycomb					3.32
Observed Zepo excess reactivity					2.6

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Fig. 1.19.

Reactivity vs width of a 0.050 in. boron vane.

Fig. 1.20.

Shadowing factor vs angular separation of control rods.

Fig. 1.21.

Dependence of reactivity on length of control strip inserted into reflector.

Fig. 1.22.

Control-rod mockup in Phoebus Zepo.

Fig. 1.23.

Effect of beryllium reflector thickness and titanium torsion tubes on boron reactivity.

TABLE 1.7
CONTROL SYSTEM MOCKUPS

Mock-Up Measurement	No. Rods	Reactivity $\$$	Relative Span	Predicted Total Span, $\$$
A. 8-in. Beryllium				
1. Clean reflector and interface	18		1.10	9.3
	24	+ 1.4	1.29	10.8
B. 7-in. Beryllium				
1. Clean reflector and interface	24	0	1.00	8.4
2. 120 titanium torsion rods 27.4 kg titanium	24	- 0.9	0.87	7.3
3. 120 Inconel torsion rods 51.6 kg In-718	24	- 0.9	0.90	7.6
4. Inconel leaf springs 86.4 kg In-718	24	- 1.6	0.93	7.0
5. Control can material				
3.52 kg titanium/drum	24	- 2.2	0.83	7.0
6.00 kg stainless steel-347/drum	24	- 1.5	0.87	7.3

Fig. 1.24.
Boron-copper effectiveness in Zepo reflector.

C. Phoebus-2 Zepo: Core Design II.

Early in the Phoebus-2 program the 12-sided core design lost favor and emphasis was shifted to an edge fuel-element arrangement fitted to a circular periphery. The Zepo aluminum can was modified and the core geometry changed to correspond with this new concept.

1. Phoebus-Zepo Revisions. The Phoebus-Zepo core and interface regions were modified to bring the system into line with changes in the reactor design. Material

changes associated with the conversion from a 12-sided core periphery to a circular periphery are listed in Table 1.8. The perimeter core elements were rearranged and an additional 18 elements were added (4789 total) to form the circular configuration shown in Fig. 1.25. The predicted reactivity increase of 1.1\$ compares with 1.25 observed. Details of the new version of Zepo were compared with the projected Phoebus-2 reactor to get a rough prediction of the reactor reactivity. This comparison appears in Table 1.9. One major deficiency in the mockup was low carbon density that was later corrected by adding graphite filler rods into the one-hole elements. The inlet end was simulated reactivity-wise by a stainless steel and aluminum structure on which the core rested inside its aluminum can.

2. Reactivity Contributions of Core Materials. Although most effectiveness measurements of core materials in Zepo as a function of radius were actually made in the 12-sided core assembly, it was assumed that results applied also to the cylindrical core. Axial reactivity variation was checked in the latter core.

a. Radial Reactivity Measurements. For uranium measurements, fuel elements with various loadings and unloaded elements were interchanged at different radial positions. As shown in Fig. 1.26, the sensitivity of reactivity coefficient to the size of fuel-loading change was large near the core surface, but disappeared as the axis was approached.

The radial values for graphite, Fig. 1.27, represent the effect of inserting 1/4-in.-diam graphite rods into channels of the Zepo elements.

Niobium reactivity coefficients were measured at 25, 75, and 100 g Nb/element as a function of radius by inserting 25- and 75-g tubes of the material. Data appear

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TABLE I.8
PHOEBUS-ZEPO DODECAGONAL-TO-CIRCULAR CHANGE

Material	Weight in kg		Δm kg	Predicted $\Delta k, S$
	Dodecagonal	Circular		
1. Aluminum				
Cylinder	690	549	- 141	
Plates	102	51	- 51	
			- 191	- 0.2
2. Graphite				
Plates	106	221	+ 115	+ 1.1
3. Fuel Region				
Uranium			+ 0.49	+ 0.1
Graphite			+ 8.9	+ 0.1
Overall predicted reactivity change				1.1
Observed reactivity change				1.2

Fig. 1.25.
Circular core configuration.

TABLE II.9
REACTIVITY CHANGES:
PHOEBUS-ZEPO TO FINAL PHOEBUS-2 REACTOR

Reactor Differences	Reactivity Change, S
1. Control system	+ 0.3
2. Tantalum shimming	- 3.0
3. Core carbon content	+ 4.5
4. Niobium self shielding	- 1.2
5. End tips and support blocks	+ 2.4
6. Beryllium reflector	+ 0.1
7. Multizone vs three-zone loading	- 0.8
8. Interface region	+ 0.8
9. Inlet end features	0
10. Support tubes (Inconel)	- 1.0
11. Core compression	+ 0.1
Predicted available reactivity	+ 2.2

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Fig. 1.26.

Uranium reactivity vs radius for various incremental changes.

Fig. 1.27.

Graphite effectiveness vs radius in Zepo.

in Fig. 1.28 with comparable Honeycomb results. Figure 1.29 shows overall reactivity contribution of niobium as a function of loading, and the corresponding core-average reactivity coefficient.

The effectiveness of niobium in actual fuel elements was compared with the above results by inserting liner tubes into the flow channels of unlined 19-hole elements. These measurements, made at only two radii, gave the dashed curve shown in Fig. 1.28. Experimental coefficients

Fig. 1.28.

Niobium effectiveness vs radius in Zepo.

Fig. 1.29.

Core average niobium reactivity as a function of coating weight.

in Honeycomb assemblies with various C/U ratios are included to illustrate general consistency with the Zepo results.

The 19-hole fuel elements were also used to check hydrogen reactivity as a function of radius. Polyethylene threads (0.076-in.-diam) were inserted into flow channels

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in various radial zones to obtain the curve shown in Fig. 1.30.

Core-average reactivity coefficients for Zepo and the similar Honeycomb assembly are compared in Table 1.10. Inconel-718 and Inconel-600 reactivities were measured by inserting rods or tubes into each support element in a sector of the core. Molybdenum wires (0.005-in.-diam) were inserted into the 19 flow channels in 50 elements at the center of Zepo giving a value of -17¢/kg. Use of the variation with radius that was observed in Honeycomb results in the value of -9¢/kg for the reactivity of molybdenum distributed uniformly.

Reactivity changes associated with radial displacement of the core outer surface were measured for six

portions relative to the aluminum reflector cylinder. Starting with fuel elements initially quite loose, the core was compressed in steps by adjusting screws through the aluminum cylinder. The curve shown in Fig. 1.31 indicates that the core is not compressed uniformly throughout the range of measurement. The asymptotic value of the radial coefficient appears to be close to 1.3\$/in.

b. Axial Reactivity Measurements. Effectiveness values for graphite, uranium, and niobium were measured along the axis of the Zepo core (without an exhaust end mockup). Results appear in Figs. 1.32, 1.33, and 1.34. The uranium and niobium samples, foils of metal rolled up to form slugs, were moved within holes in the Zepo elements. Because of some self-shielding in these samples, the average values in Figs. 1.33 and 1.34 are normalized to unity. Graphite samples were larger and longer solid cylinders inserted into spaces vacated by removing support elements. The point marked "A" in Fig. 1.32 resulted from a measurement in which 1-in.-long pieces of support element were added to the top of the core. For the point marked "B," all the support elements were raised 1 in. Both points have been corrected to an on-axis location. The disagreement with Honeycomb results (Fig. 1.32) may be due to streaming in the larger Honeycomb channels. The axial averages from these graphite profiles agree well in both cases with the values obtained by direct measurement with full-length elements.

3. Inlet-End Measurements. Much effort went into simulating the Phoebus-2 inlet-end conditions on Zepo because of concern that a high fission-density there would

Fig. 1.30.
Hydrogen reactivity vs radius in Zepo.

TABLE 1.10

CORE-AVERAGE REACTIVITY COEFFICIENTS

Material	Reactivity, ¢/kg	
	Zepo	Honeycomb
Uranium	7.7	7.2
Graphite	2.8	3.0
Niobium		
Single tube/element, 75 g	-3.2	-2.5
19-tubes/element, 75 g	-3.6	
Inconel		
Type 718	-0.9	
Type 600	-0.5	
Molybdenum	-9	
Hydrogen	420	490

Fig. 1.31.
Reactivity change due to Zepo core compression.

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Fig. 1.32.
Graphite reactivity vs axial station.

Fig. 1.33.
Uranium reactivity vs axial station.

result in temperature too high for the aluminum orifices. With an 8-in.-thick aluminum support plate flooded with high-density hydrogen, it was expected that effective poison plates would be required to minimize the inlet-end fission peaking. Poison plates were mocked up with a boron-plastic material until production boron-copper poison plates were available.

The overall inlet mockup shown in Fig. 1.35 was added to the top of the Zepo core. Material weights listed in Table I.11 were as nearly as possible those anticipated for the reactor, although detailed structure was not reproduced. Reactivities in Table I.12 were measured as the components were added in the order listed. Hydrogen (in polyethylene), introduced without inlet poison, was worth +41¢. This would indicate a value of -47¢ for the poison plates when added after the hydrogen, and

Fig. 1.34.
Niobium reactivity vs axial station.

Fig. 1.35.
Phoebus-2 inlet-end schematic.

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TABLE I.11
PHOEBUS-ZEPO INLET MOCKUP

Region	Material	Weight, kg
Core	Hydrogen (projected)	1.4
	Stainless steel	240.
Plenum	Hydrogen	1.5
	Carbon	9.0
	Aluminum (orificing)	14.7
	Stainless steel	79.6
Support Plate	Hydrogen	1.4
	Carbon	8.5
	Aluminum	643.

Fig. 1.36.

Axial variation of aluminum and stainless steel reactivity in the inlet mockup.

TABLE I.12
ACCUMULATED REACTIVITIES OF INLET MOCKUP

Component	Reactivity cents
Stainless steel and aluminum plenum and support plate	230.
Aluminum orificing	7.5
Poison plates (boron-copper) ^a	- 12.0
Plenum hydrogen	6.2
Support plate hydrogen	0.1
Total	232.

^aThis value is computed from that for the plastic, correcting for differences in hydrogen, carbon, and copper.

demonstrates the decoupling function of the absorber for moderator materials.

After addition of the inlet mockup to the Zepo assembly, differential measurements with aluminum and stainless steel gave reactivity coefficients as functions of position. These differential data, plotted in Fig. 1.36, apply to modest changes in material content from that contained in the mockup. Core-hydrogen reactivity was measured with the inlet-end mockup in place by special step-tapered polyethylene strings that gave the proper variation of hydrogen density along a fuel element. A single string per fuel element gave the equivalent of the operational hydrogen density to the precision shown in Fig. 1.37. For the density comparison it was assumed that the hydrogen in the polyethylene was distributed

Fig. 1.37.

Phoebus-Zepo core hydrogen mockup.

throughout the flow volume. Strings with a different taper were fabricated to mock up hydrogen in support tubes. For comparison, additional measurements were made without the inlet-end mockup, and with both uniform and tapered polyethylene strings. Figure 1.38 shows

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Fig. 1.38.

Radial dependence of hydrogen reactivity.

that the data were only slightly affected by the inlet-end mockup. Uniformly distributed hydrogen was worth 4.1S/kg whereas axially tapered hydrogen was worth 79% as much. Hydrogen in the tubes is much more uniform with length than fuel-element hydrogen, and reactivity-wise the hydrogen was worth about 4S/kg.

Fission density at the inlet end of fuel elements was of concern because of the low-melting-point aluminum orifices. Thus, it was imperative that reliable measurements be made with a more detailed mockup of actual conditions. It was felt that fission densities at fuel element ends higher than 40% of the central value might cause trouble.

There were practical problems in adding a complete mockup of core hydrogen worth ~4S in reactivity, so it was assumed that valid on-axis fission distributions could be obtained with hydrogen confined to a small zone about the axis. This distribution was expected to give the greatest inlet fission density. Thus, hydrogen was mocked up in the core in an axial zone ~18 in. in diameter by means of the tapered polyethylene threads inserted into fuel elements and support elements. Polyethylene distribution in the plenum and support-plate regions was designed to simulate hydrogen in the test reactor. Boron plastic sheets used to simulate inlet poison plates in preliminary measurements had boron surface density equivalent to that in the ~0.050-in.-thick boron-copper plates planned for the test reactor. The boron plastic was available both as a uniform sheet and as a relatively precise mockup including the appropriate hole distribution and void fraction, so that comparison would give the effect of holes. Figure 1.39 shows the boron plastic material that covered the entire core, and some actual boron-copper poison plates that covered only the ends of fueled elements in the central section.

Axial fission profiles for the various inlet-end conditions listed in Table I.13 were determined by scans with a small, remotely driven, solid-state fission counter.

Fig. 1.39.

Boron plastic and boron-copper poison plates.

TABLE I.13

INLET-END FISSION DISTRIBUTION CONDITIONS

Profile Number	Poison Plate Mockup	Surface Density B, g/cm	Hydrogen Mockup
1	none	0	yes
2	Single layer perforated	0.036	yes
3	Double layer perforated	0.072	yes
4	Single layer solid	0.068	yes
5	Double layer solid	0.136	yes
6	none	0	no

Results of the scans, normalized by a fixed monitor counter, are summarized in Fig. 1.40. Curve No. 6 was obtained by gamma scanning a fuel element following an activation run. Figure 1.41 indicates the dependence of inlet fission level intercept on total boron content whether or not holes are present in the mockup.

For the final prediction of inlet-end fission distribution, the boron plastic poison plate mockup was replaced by production-type B₄C-Cu alloy over a 13-in.-diam central region with the plastic mockup extending over the remainder of the core. The differences in results of measurements with the alloy and with the mock-up material were minor, even though B₄C-Cu plates covered only the fueled elements and hydrogen in the boron plastic resulted in a somewhat different hydrogen distribution. Results of experiments made for various conditions of hydrogen in the core and inlet support region are summarized in Fig. 1.42. The configuration for Curve B3 was designed to approximate that at full-power conditions.

Selected data appear in more detail on an expanded scale in Fig. 1.43. In Zepo the fuel elements and unloaded

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Fig. 1.40.

Phoebus-2 Zepo, inlet-end fission distribution with various poison-plate configurations.

Fig. 1.41.

Phoebus-Zepo inlet-end fission intercept vs boron density in poison plate.

Fig. 1.42.

Phoebus-Zepo inlet-end fission profiles.

Fig. 1.43.

Detail of inlet-end fission profiles.

elements are identical in length (52 in.), whereas in the Phoebus-2 design the support elements extended beyond the poison plates into the plenum region. When this feature was mocked up in Zepo, it was found to have little influence on inlet fissions as shown by Curve 3. Curve 4 shows that the fissioning flux is relatively the same in unloaded elements as in fuel elements even though the ends of these elements are not shielded with B₄C plates.

4. Exhaust-End Measurements. The axial fission profiles in the Zepo core were observed with various mockups of exhaust-end structures. These include the bare core, with 1-3/8 in. of unloaded end tips added, and with end tips plus various support block structures. Fission profiles were recorded by scanning fuel elements with a well-collimated crystal scintillation detector.

The Phoebus-2 design called for 52-in.-long fueled elements with unloaded glued end-tips for transition to some support block structure. The various mockups of exhaust-end configurations that were investigated are described in Table I.14. A typical fuel-element fission scan is shown in Fig. 1.44, corrected for decay and the indicated background radiation leaking through the collimator shielding. Figure 1.45 shows the effects of various exhaust-end mockups on fissions near the end of the core. The effect of the exhaust-end configuration on adjacent fissions appeared to depend almost entirely upon the amount of graphite in the mockup and to a minor degree upon other material. This is very evident in Fig. 1.46

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TABLE 1.14
PHOEBUS-2 EXHAUST-END MOCKUPS

Mockup Components ^a	Thickness in.	Void %	Weight of Materials, kg					Reactivity, \$
			C	Nb	Ta	Inc718	Mo	
(1) Bare core end								0
(2) Unloaded end tips	1.37	33.7	58.2	9.12		2.71		1.0
(3) Support blocks (uncoated)	2.50	40.0	100.9					
(4) Support blocks (Ta-coated)	2.50	36.6	100.9		24.7	14.0		2.3
(5) Support blocks (Nb-coated)	2.50	36.1	100.9	16.7		14.0		2.4
(6) Support blocks (Kiwib-B-4 type)	1.50	30.4	66.8	9.53		3.98	1.48	
(7) Variation of 2 + 5	1.37	33.0	58.2	12.2		2.71		
	2.50	33.2	100.9	40.1		14.0		

^a(3), (4), (5), and (6) were added to (2).

Fig. 1.44.

Fuel element gamma scan corrected for leakage through the collimator.

Fig. 1.45.

Effects of various exhaust-end mockups on axial fissions.

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Fig. 1.46.

Exhaust end fissions vs amount of graphite added to bare core.

where end fissions are plotted against carbon content of the various mockups.

Finally, the predictions of inlet-end and exhaust-end axial fission variation are combined in Fig. 1.47 for operating conditions. Although much effort went into representing inlet-end and core hydrogen realistically, the effects of temperature are not included because there was no way to simulate them. This on-axis fission distribution is the limiting case in the sense that the fission distributions along outer elements drop off more rapidly. The fission profile in Fig. 1.47 was represented empirically by

Fig. 1.47.

Axial fission profile predicted for Phoebus-2 under operating conditions.

a sine relation modified at each end by the addition of an exponential. The following equation matches experimental data closely.

$$F = \sin(0.049Z + 0.352) + 0.0726e^{-0.390Z} + 0.038e^{-0.329(52-Z)}$$

D. Phoebus-2 Zepo: With Production Reflector and Fuel

1. Critical Conditions and Fission Profile for Initial Loading. The Phoebus-2 Zepo configuration was revised by replacing the universal beryllium reflector with the actual Phoebus-2 reflector and inserting a 90° core sector of production fuel elements. Table I.15 compares the old configuration with that represented by the 90° test sector. Initial measurements were concerned primarily with reactivity, control-rod worth, and fission distribution.

The new reflector and control system (18 control rods at 180°) with associated hardware contributed 1.6\$ less reactivity than the earlier unpoisoned reflector. Because each control vane at 180° poisoned the reactor by 6.0c, the new beryllium alone was 0.5\$ less reactive. The Zepo core criticality was increased ~7\$, in steps, by adding graphite and removing the tantalum elements. During this process, as the control-rod setting at critical changed from 180 to 60°, the control-rod effectiveness varied as shown in Fig. 1.48. These curves extrapolate to a control-rod span of 8.6\$ when fit with a sine function. Measurements of shutdown, taken with a reactivity meter, indicated the span to be more like 9\$. Various further

TABLE I.15

PHOEBUS-2 ZEPO MODIFICATIONS

Region	Core II Configuration, kg	New Reflector 90° Test Section Projected over 360°, kg
Core		
Uranium	294	273
Carbon	2267 ^a	2420
Niobium	298	305
Interface		
Carbon	221	321
Aluminum	600	679
Invar	---	20.6
Reflector		
Beryllium	2414	2439

^a An additional 148 kg of carbon was added to the core before stacking the test sector for a total core carbon weight of 2415 kg.

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Fig. 1.48.

Response of Phoebus-Zepo control system.

modifications of the Zepo mockup improved simulation of Phoebus-2. The effect of these changes on the control-rod response was monitored by considering the 0 to 180° span of a single rod (with the two adjacent rods fixed at 90°) as a "figure-of-merit" of the control system. The apparent control span variations as the mockup was altered are summarized in Table I.16. Before measuring a fission distribution, the system was adjusted to critical at ~90° by inserting 14 tantalum shim elements for each 60° section (2.5\$ worth), uniformly distributed over the regular clusters.

The fuel-element loadings in mg/cm³ in 60° of the 90° test sector (Fig. 1.49) were chosen to make the power density as flat as possible with available fuel elements on the basis of a computed fissions/g-U distribution. The fissions/g-U profile of Fig. 1.50 is the result of counting the fission fragment beta activity of U-Al flux wires irradiated at the core midplane. The power density

distribution shown in Fig. 1.51 was obtained by applying computed cold-to-hot corrections to this fission distribution and by including the effects of gamma and neutron heating. The droop at the edge of the core was the consequence of adjusting the Zepo fuel to match a fission distribution computed earlier in the Phoebus-2 studies when 3\$ of boron in the reflector was assumed for the critical point instead of the actual 5\$ consistent with ~90° control rod setting.

2. Preliminary Operating Power Distribution. Because the initial Zepo test sector stacking did not give the desired flat power, a different loading distribution was required for Phoebus-2. For this relatively large modification in loading it could not be assumed that the fissions-per-gram curve measured in Zepo was valid. A correction to the experimental curve (Fig. 1.50) was obtained by comparing calculations representing the Zepo loading with calculations representing a flat power loading. The preliminary power-per-gram curve of Fig. 1.52 is the result of applying this computed correction and the cold-to-hot factors to the measured flux. The data for corrections to cold fissions-per-gram along with cold-to-hot factors and the resulting hot power distribution are presented in Table I.17.

3. Measurements with Revised Loading. Based upon Fig. 1.52, fuel elements in the Zepo test sector were redistributed to compensate for the droppoff in fission density near the edge of the core. The second loading distribution gave approximately the desired fission density distribution. The uranium inventory, however, dropped to ~276 kg rather than the designed 300 kg, because of the limited supply of elements available. The 90° test sector loading was now considerably different than the

TABLE I.16

EFFECT OF ZEPO MODIFICATIONS ON CONTROL RANGE

Modification to Previous Step	Single Rod Span, \$	Relative Effect of Single Modification	Estimated Control Rod Span, \$
Initial sector stacking	45.95		8.60
100 kg carbon added to interface	47.03	1.02	8.80
20 kg Invar added to above	45.67	0.97	8.55
2½\$ of tantalum added to core	42.27	0.93	7.91
1.5 kg axially uniform hydrogen added to interface	42.59	1.01	7.97

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Fig. 1.49.
Initial loadings in Phoebe-2 Zepo test sector.

remainder of the core containing one-hole Zepo fuel elements, therefore, the one-hole elements were also redistributed. With various combinations of the 100, 200, 300, and 400 mg uranium loadings, the integral of fuel loading in the 270° sector was matched grossly to the 90° sector at all radii.

a. *Fission Distributions.* Flux wires inserted into the central flow channels of selected fuel elements were used to monitor the change in fissioning flux in the test

sector accompanying the core modifications described above. Both the revision of the 90° sector and of the 270° sector caused significant changes in the fissions/g-U radial distribution, as shown in Fig. 1.53. To obtain similar rod settings (~94°) for the three different configurations considered, reactivity was adjusted by adding graphite plates to the top of the core. A uniform graphite end reflector was expected to have a small effect on the radial fission distribution.

After modification, fuel elements were activated

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Fig. 1.50.

Fission distribution in Phoebus-2 Zepo.

Fig. 1.52.

Phoebus-2 hot power distribution.

Fig. 1.51.

Hot power density deduced for initial Phoebus-2 Zepo loading.

and gamma-counted to obtain a fission distribution for the 60° test sector. This configuration contained ~2\$ worth of tantalum shim elements, distributed one for each seven clusters near the axis, and 2½ in. of graphite at the top of the core (a reasonable mockup of unloaded end tips and support blocks). Resulting fissions/g-U for each fuel element are plotted in Fig. 1.54, and the corresponding fission density is shown in Fig. 1.55.

The minimum in the fission distribution shown in Fig. 1.54 was ~15% lower than that which had been used to specify the loadings of Phoebus-2 fuel elements that were being fabricated. As a result, the available loadings were not optimum. It was possible to improve this situation by concentrating tantalum shim elements near the

center of the core, but unfortunately the exact number of tantalum elements required for reactivity shimming could not be known until the Kiva checkout of the reactor. It was assumed that one iteration of the initial Phoebus-2 loading would be required during this checkout, but this was not necessary.

4. Fission Fine Structure Measurements. Fission measurements in the Phoebus-Zepo test sector were directed at establishing Q_{mean} (Q_M) and Q_{hole} (Q_H) factors for every fuel element in the core, where Q_M is the average fissions-per-gram-U for an element relative to a central element, and Q_H is the fission density at each hole in an element relative to the average value for the element. The Q_M factors used for specifying the initial Kiva loading distribution for Phoebus-2 were based on the data of Fig. 1.55 from gamma counting of Zepo fuel elements. Corrections to this basic Q_M distribution were obtained from measurements with U-Al flux wires.

A total of 36 Zepo irradiations of flux wires (97 wires each) were run to determine the Q_H factors and to study the perturbing effects of regular and tantalum-loaded support elements, control rods, hydrogen in tie tubes, and thermocouple carrier elements. The Q_H factors were measured in the central and six corner flow channels of an element and determined by interpolation for the remaining 12 channels. Each of the 107 elements in the irregular peripheral clusters was mapped individually, whereas less complete sampling was required for elements in regular clusters.

a. Support element and Thermocouple Carrier Element Perturbation. The fission distribution in the regular cluster region of the reactor can be described by a smooth radial function with bumps (or depressions) superimposed by the local effect of support elements, thermocouple carrier elements, and off-design loadings. To isolate perturbing effects, Q_H factors measured with flux wires were compared with idealized Q_H factors that would exist if the perturbation were absent.

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TABLE 1.17
PHOEBUS-2 POWER DISTRIBUTIONS AND HOT:COLD FACTORS

Radius, in.	Measured Fissions/g	Calculated Correction Factor	Hot:Cold Fission Ratio	$\gamma + n$ Heating	Hot Power/g
0	1.000	1.000	1.000	1.000	1.000
1	1.000	1.000	1.000	1.000	1.000
2	0.999	1.000	1.000	1.000	0.999
3	0.990	1.000	1.000	1.000	0.990
4	0.978	1.000	1.000	1.000	0.978
5	0.959	1.001	1.000	1.000	0.960
6	0.938	1.001	0.999	1.000	0.938
7	0.913	1.002	0.999	1.000	0.914
8	0.890	1.002	0.998	1.000	0.890
9	0.862	1.004	0.998	0.999	0.862
10	0.833	1.005	0.997	0.999	0.834
11	0.802	1.006	0.996	0.999	0.803
12	0.770	1.005	0.995	0.998	0.769
13	0.738	1.005	0.993	0.998	0.735
14	0.705	1.004	0.992	0.998	0.701
15	0.669	1.000	0.991	0.997	0.661
16	0.634	0.998	0.989	0.997	0.624
17	0.598	0.994	0.987	0.996	0.584
18	0.563	0.989	0.985	0.996	0.546
19	0.531	0.984	0.983	0.995	0.512
20	0.505	0.979	0.982	0.993	0.482
21	0.486	0.971	0.983	0.992	0.460
22	0.486	0.960	0.985	0.990	0.455
23	0.509	0.940	0.990	0.987	0.467
24	0.574	0.909	0.997	0.983	0.512
25	0.701	0.888	1.007	0.978	0.613
26	0.925	0.901	1.019	0.971	0.824
27	1.280	0.945	1.050	0.960	1.220
28	1.800	0.961	1.130	0.945	1.847

Fig. 1.53.

Ratio of fissions for various core configurations.

In the case of support elements, both regular and tantalum loaded, the unperturbed Q_H values were obtained analytically from the smooth plot of Q_M vs radius. Perturbation factors deduced for regular support elements are shown in Fig. 1.56 for an element in one orientation. This pattern was simply rotated around the element for the other five orientations in the cluster. The magnitude of support element perturbation was found to be radially dependent, increasing with radius as shown by the equation in the figure. Tantalum-loaded support elements gave somewhat less perturbation but data were hardly precise enough to distinguish them from regular supports. They were investigated in more detail during the Kiva checkout.

Thermocouple carrier elements substituted for fuel elements in seven locations were essentially the same as adjoining support elements and resulted in a double

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Fig. 1.54.

Relative fissions/gram from Phoebus-2 Zepo fuel element counting.

Fig. 1.55.

Relative fission density from Phoebus-2 Zepo fuel element counting.

Hole	Support Element Perturbation
1 - 1	$P_1 = 0.998$
2	0.995
3	0.994
4	0.990
5	0.996
6	0.996
7	0.995
8	0.997
9	0.997
10	0.997
11	0.997
12	0.997
13	1.004
14	1.004
15	1.014
16	1.004
17	1.011
18	1.011
19	1.011

$$\frac{\text{perturbed } Q_M}{\text{unperturbed } Q_M} = P_1 + (P_1 - 1)(R_1 - 7.875)/28.875$$

where R_1 = radius from core center

Fig. 1.56.

Support element fission perturbation in Phoebus-2.

Fig. 1.57.

Effect of thermocouple carrier elements on Q_M values of adjacent fuel elements.

perturbation on the five touching fuel elements. Phoebus-1B measurements had shown that this perturbation, within the limit of resolution, was identical to that from a support element. In addition to the effect on Q_H , the thermocouple carrier elements introduced a general boosting in Q_M in adjacent fuel elements. Measurements showed that this boosting was also radially dependent as may be seen in Fig. 1.57.

b. Perturbation Due to Off-Loaded Elements. In several locations within the core, it was planned to include clusters of WANL test elements with NRX fission densities. Loadings in these elements were to be ~ 0.6 of the regular loading for that location. Measurements in

Zepo showed that this reduction in loading introduced a flux "bump" that averaged $\sim 5\%$ over the WANL elements and extended into the adjacent elements. Table 1.18 lists the ratio of loadings for six test elements in the "NS" cluster and the resulting boost in fissions per gram due to the reduction in loading. Figure 1.58 shows the flux peaking as a function of distance from the center of the simulated WANL cluster, and Fig. 1.59 gives the resulting perturbation factors and the boost in Q_M .

c. Perturbation Due to Tie-Tube Hydrogen. Because there was to be considerably more hydrogen in tie tubes than in fuel elements during full-power operation,

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TABLE I.18

EFFECT OF SIMULATED WANL ELEMENTS
IN PHOEBUS-2

Location	Fuel Element Loadings		Ratio	Fiss/g ratio
	Zepo	WANL		WANL Elements
				Zepo Elements
NSB	350	206	0.59	1.046
NSC	352	208	0.59	1.041
NSD	319	196	0.61	1.052
NSE	319	191	0.60	1.054
NSF	352	214	0.61	1.066
NSG	355	213	0.60	1.067

Av: 1.054

Role	Perturbation Pattern Factors		
	Element I	Element II	Element III
1	0.9913	0.9868	0.9850
2	0.9913	0.9878	0.9859
3	0.9913	0.9868	0.9908
4	0.9961	0.9927	0.9889
5	0.9979	0.9937	0.9928
6	0.9979	0.9937	0.9966
7	0.9961	0.9927	0.9966
8	1.0008	0.9986	0.9908
9	1.0017	0.9985	0.9966
10	1.0027	1.0005	1.0005
11	1.0017	0.9995	1.0044
12	1.0008	0.9986	1.0063
13	1.0036	1.0064	0.9986
14	1.0046	1.0074	1.0044
15	1.0048	1.0074	1.0092
16	1.0036	1.0064	1.0121
17	1.0046	1.0132	1.0063
18	1.0046	1.0152	1.0121
19	1.0046	1.0132	1.0170
Q_M ratio	1.0542	1.0245	1.0355

Fig. 1.59.

Fission fine structure perturbation due to two clusters of WANL elements.

Fig. 1.58.

Fission boosting due to two clusters of elements with 60% normal loading.

experiments were run to check the influence of this hydrogen upon surrounding fissions. To obtain a significant effect, flux wires were irradiated in adjacent elements with double and quadruple the normal amount of tie-tube hydrogen mocked up by polyethylene strings. The conclusion was that tie-tube hydrogen did not produce a significant fission perturbation.

d. Radial Perturbation Due to Tantalum-Loaded Shim Elements. The basic Zepo measurements that established Q_M were made with tantalum elements distributed in regular clusters in a pattern consisting of one tantalum support element for every seven clusters. This dilute geometry had the advantage that modifications in the number of tantalum elements in the core introduced minimal change in the radial fission profile. Later, it

appeared advantageous to tailor the fission distribution by concentrating the required shim elements in the central region. This arrangement had the effect of reducing the center-to-minimum fission ratio to one more suitable for the inventory of fuel-element loadings available for the reactor. Wire data shown in Fig. 1.60 for the two extreme conditions, concentrated vs dilute, show the range of tailoring possible. The 1.8% of reactivity shimming corresponded to 37 central or 55 dilute tantalum elements.

e. Control-Rod Perturbation. The fission profile near the edge of the Phoebus-2 Zepo core was examined with control rods at 96° and with the rods shifted $\pm 2.1\%$ from that setting. Flux-wire measurements were made in elements along a radial line intersecting a control vane and along a line midway between two control vanes. The

Fig. 1.60.

Comparison of Phoebus fission distribution with different tantalum-element configurations.

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resulting data points shown in Fig. 1.61 were each derived from a pair of measurements in a single fuel element with seven flux wires. The critical control-rod setting was adjusted in 2.1\$ steps by the different combinations of tantalum shimming and graphite end reflector shown below.

Critical Rod Position	Reactivity	
	Ta-Elements	End Reflector
65°	0	2.1\$
96°	0	0
96°	-2.1\$	2.1\$
130°	-2.1\$	0

Thus, for each pair of control-rod settings compared, 65°:96° and 96°:130°, the only difference, other than rod position, was the end graphite reflector. It was assumed that a uniform end reflector had a minor effect on the shape of the radial fission profile.

The data seem to indicate no sensitivity to azimuth and perhaps a slight difference between the 65°:96° and 96°:130° changes. On the assumption that the magnitude of the flux change accompanying a change in control-rod position scales with the reactivity involved, the curve per dollar of reactivity was deduced.

E. Kiva Checkout

1. Overall Criticality. The Phoebus-2 Kiva assembly was initially critical at 115° on the control drums without the pressure vessel and nozzle, and lacking ~20 kg of graphite and 50 kg of tungsten-molybdenum from the support-block region. A comparison between the Kiva assembly and Phoebus-2 Zepo appears in Table 1.19. In

this table, experimental reactivity coefficients have been applied to predict the reactivity difference between Phoebus-2 and Zepo. The loss of 2.68\$ in reactivity from Zepo to the Kiva assembly would imply a shift of the 96° critical setting of Zepo to 140° for Phoebus-2—a discrepancy of 25° with the observed value.

The effect of core instrumentation on reactivity was not known with any degree of confidence. The thermocouple wires and sheaths are resonance poisons, whereas the BeO insulation contributes reactivity. To improve estimates of thermocouple reactivity, 20 W-Re-W "station-20" thermocouples were checked near the center of Parka. The 18-in.-long molybdenum-sheathed sections were centered, with ~17 in. of the stainless steel lead-in in the core. Reactivity loss due to the 20 thermocouples was observed to be only 2.2¢.

Phoebus-2 was taken through the following series of critical configurations during the Kiva checkout.

- (1) Without pressure vessel and nozzle, and lacking 20 kg of graphite and 70 kg of tungsten-molybdenum from the support-block region—control drums at 115°.
- (2) Twenty kilograms graphite added, otherwise same as (1)—control drums at 113°.
- (3) Pressure vessel added, otherwise same as (2)—control drums at 111°.
- (4) Nozzle added, otherwise same as (3)—control drums at 105.5°.
- (5) Additional 195-kg graphite on exhaust end, otherwise same as (2)—control drums at 95°.

The purpose of the additional graphite in the final configuration was to attain the control-drum setting expected under operating conditions, so that control-rod perturbations would not enter the correction of the cold fission distribution to hot conditions.

The differential control-rod worth was obtained for the Kiva assembly by positive-period and K-meter measurements that were in good agreement. The curve shown in Fig. 1.62 is the result of fitting the data with two segments of sine curves that meet at 88.4° with an amplitude of 6.41¢/degree. The resulting integral rod-worth of 7.3\$ was slightly less than had been estimated in Zepo.

2. Prompt-Neutron Lifetime. The prompt decay constant of the reactor was measured by means of a pulsed neutron source. Because the internal α, n source from carbon gave a high background, it was necessary to pulse intermittently, allowing the neutron level to decay between the pulsing intervals by inserting two fast control rods. During pulsing, the power level was allowed to change a factor of two as data were collected with the reactor 6.2¢ supercritical. After subtraction of background, the composite neutron decay following pulses

Fig. 1.61.

Edge fission perturbation by control rods.

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TABLE I.19
PREDICTION OF PHOEBUS-2 REACTIVITY FROM ZEPO MEASUREMENTS

Material	Weight, kg ^a			¢ /kg	Δk ¢
	Ph-2	Zepo	Δm		
Core					
Carbon	2418	2408	10	2.8	+ 28
Uranium	297	274	23	7.0	+ 161
Niobium					
Fuel elements	328	85	243	- 3.6	- 875
Support elements	24		24	- 3.6	- 86
Core edge	3		3	- 2.0	- 6
Zepo tubes		237	- 237	- 3.2	+ 758
Tantalum shim elements	0 ^b	31 ^b			- 150
Inconel	165	47	118	- 0.94	- 111
Molybdenum	12	0	12	- 11	- 132
					- 413

^a For 52 in. length fuel section.					
^b Number of tantalum elements.					
Core Edge and Interface					
Carbon					
Fillers	110				
Pyrolytic graphite	39				
Slats	106				
	255	322	- 67	1.0	- 67
Load rings	45		45	0.7	+ 32
					- 35
Exhaust End					
Tips and Support					
Blocks	yes	no			+ 180
Grand Total					- 268

^aFor 52 in. length fuel section.
^bNumber of tantalum elements.

was the exponential of Fig. 1.63. This decay gives an α value of 173.5 sec^{-1} . From

$$\ell = \frac{1 - k_p}{\alpha}$$

where $1 - k_p$ at $6.2c$ above delayed critical is 0.938×0.0072 , the prompt lifetime is $38.9 \mu\text{sec}$.

3. Fission Distribution. Fine-structure fission measurements were mostly confined to the Zepo assembly and only check measurements were made during the Kiva assembly. The Q_H factors from Zepo were confirmed for a selection of peripheral elements. Similarly, the

control-rod perturbation was remeasured and found to be in agreement with the previous results. Activations of flux wires (7.5 in. centrally located) irradiated in configurations 1 and 5 were compared to obtain the effect of a control-rod change from 95 to 115° . The data, appearing in Fig. 1.64, are in agreement with the Zepo results.

The final fission activation to establish Q_M values for each element in the core was run at 4.1 kW for 20 min . To supplement gamma counting of the elements, a distribution of 7.5-in. flux wires and several full-length (52 in.) wires was included. The 7.5-in. wires were to provide a comparison with a set to be run later at NRDS for a final check on the cold fission distribution in the testing environment. The full-length wires were included

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Fig. 1.62.
Phoebus-2A control-rod response.

Fig. 1.64.
Ratio of fission density with control rods at 115° to that at 95°.

to derive a factor to convert from 7.5-in. wires to full-length wires. A second factor was obtained from the Q_H data to convert from central-channel-wire data to fuel-element averages. The resulting factors (Fig. 1.65) indicate that 7.5-in. wires require several percent correction at the core edge to represent fuel-element fissions. The observed normalized ratio of midplane wires (7.5 in.) to fuel-element activities in Fig. 1.66 should be the product of the two factors in the previous figure (the solid curve in Fig. 1.66). Because agreement is only fair, wire measurements are considered somewhat questionable.

Fig. 1.63.
Prompt neutron decay in Phoebus-2A.

Fig. 1.65.
Comparison of flux wire and fuel element fissions.

Two complete 60° sectors of fuel elements were gamma counted to establish Q_M values for every location in the core. The resulting relative fissions/g-U is plotted against radius in Fig. 1.67. Because WANL low-loaded elements were not available for the Kiva checkout, they were simulated with Parka elements having the same

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Fig. 1.66.

Ratio of midplane wires to fuel element activity.

Fig. 1.68.

Comparison of Fissions in WANL elements and adjacent elements with unperturbed elements.

Fig. 1.67.

Fission profile in Phoebus-2A from fuel element counting data.

loadings (~60% of the normal uranium content for that location). The influence of these elements on fissions/g-U can be seen in Fig. 1.68, where the circles refer to elements at reduced loading, the crosses to neighboring elements at full loading, and the solid line applies to unperturbed elements. The flux perturbation in WANL elements appeared to be a radially independent 8%, instead of the 5.4% estimated with Zepo.

4. Neutronic Predictions for Full-Power Operation.

Conditions of temperature and hydrogen coolant in the reactor at power introduce major perturbations in both the reactivity and the fission distributions that could not be simulated in the Kiva assembly. Measurements of temperature effects were not feasible so that all hot-to-cold conditions had to be compared through computations. Some effects of hydrogen in the reactor were measured by a polyethylene mockup, but the effects of chilled or hot hydrogen could not be investigated.

A control-rod setting of $\sim 95^\circ$ was arbitrarily selected as the intended hot-critical point for the test at NRDS. To compensate for the fact that corrosion would cause the rods to move out and lead to power peaking at the core edge, it was decided to aim for 90° as the initial full-power rod setting. Thus, the reactor would start with a temperature droop at the core edge that would change to a temperature peak as the test progressed. At the Kiva, the critical setting was 105.5° with pressure vessel and nozzle in place (configuration 4). The total changes between this configuration and the test, including the effects of going to power, are estimated in Table I.20. Of the 1.8\$ total, 1.0\$ corresponds to the rod change from 105.5° to 90° leaving 0.8\$ to be cared for with tantalum shim elements. The required additional shimming for NRDS, 24 tantalum elements, gave an expected cold-critical rod setting of $\sim 115^\circ$ at the test cell.

During reactor assembly at Nevada, the reactor was orificed to take into account power variations that remained after selecting the optimum distribution of fuel-element loadings. Inputs to the orificing calculation were as follows.

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TABLE I.20
COLD KIVA TO FULL POWER-CHANGES

Change	Reactivity Change, β
Computed cold-to-hot	1.6
Core changes	0.1
W-Mo end caps	0.1
Shield	0.2
Additional instrumentation	-0.2
Total	1.8

(1) Fine structure, Q_H , values from Zepo measurements.

(2) Average fissions per gram, Q_M , values from fuel-element counting.

(3) Hot-to-cold factor $f(H:C)$ from calculations.

(4) Neutron gamma heating factor, $f(n,\gamma)$, from calculations.

The relative power generation in any flow channel is given by $Q_H \cdot Q_M \cdot L \cdot f(n,\gamma) \cdot f(H:C)$, where L is the fuel-element loading. The Q_H took into account perturbation due to support elements, shim elements, WANL elements, and thermocouple carrier elements. A sample of the Q_H , Q_M data is shown in Table I.21. The predicted hot-to-cold factor was a composite of the effects of temperature changes, expansion, and hydrogen addition. The total effect appearing in Fig. 1.69 shows a 12% peak at the core edge.

Gamma-neutron heating drops off at large radii because of leakage, therefore flat power required a rising fission density at the core edge. The ratio of normalized power without the gamma-neutron contribution to normalized power without the gamma-neutron contribution is the factor $f(n,\gamma)$, which was unity at the center and dropped off to 0.95 at the core edge as shown in Fig. 1.69.

Fig. 1.69.
Temperature and gamma-neutron heating effects on power.

TABLE I.21

TYPICAL FISSION DATA FOR PHOEBUS-2A

Q_H										Q_M	ELEMENT
1 11	2 12	3 13	4 14	5 15	6 16	7 17	8 18	9 19	10		
0.9500 0.9940	0.9520 0.9990	0.9540 1.0230	0.9700 1.0230	0.9690 1.0290	0.9720 1.0340	0.9770 1.0560	0.9890 1.0620	0.9890 1.0680	0.9890	0.5695	03Q07E
0.9330 1.0140	0.9400 1.0220	0.9470 1.0080	0.9570 1.0210	0.9700 1.0390	0.9760 1.0470	0.9840 1.0360	0.9810 1.0540	0.9930 1.0720	1.0060	0.5875	03Q07F
0.9230 1.0050	0.9330 1.0270	0.9430 1.0270	0.9460 1.0330	0.9530 1.0320	0.9630 1.0540	0.9850 1.0840	0.9700 1.0830	0.9760 1.0820	0.9820	0.6784	03Q07G
0.9260 0.9930	0.9300 1.0050	0.9340 1.0370	0.9570 1.0320	0.9530 1.0360	0.9570 1.0490	0.9700 1.0850	0.9890 1.0890	0.9840 1.0930	0.9800	0.7841	03Q07H
0.9350 1.0080	0.9250 1.0220	0.9150 1.0290	0.9520 1.0410	0.9640 1.0370	0.9540 1.0520	0.9680 1.0890	0.9690 1.0850	0.9810 1.0810	0.9940	0.7312	03Q07J
0.9290 0.9980	0.9390 1.0000	0.9490 1.0290	0.9560 1.0360	0.9630 1.0330	0.9730 1.0350	0.9740 1.0760	0.9820 1.0730	0.9890 1.0700	0.9970	0.6179	03Q07K
0.8930 1.0250	0.9120 1.0400	0.9310 0.9990	0.9240 1.0270	0.9520 1.0660	0.9700 1.0810	0.9850 1.0440	0.9540 1.0830	0.9820 1.1220	1.0100	0.7002	03Q07L
0.8970 1.0080	0.9140 1.0230	0.9320 1.0280	0.9370 1.0350	0.9450 1.0490	0.9630 1.0630	0.9780 1.0770	0.9780 1.0900	0.9360 1.1040	0.9930	0.7433	03Q07M
0.8830 1.0040	0.9070 1.0220	0.9300 1.0270	0.9240 1.0370	0.9340 1.0590	0.9580 1.0770	0.9760 1.0890	0.9660 1.1110	0.9760 1.1330	0.9860	0.8892	03Q07N
0.8700 1.0040	0.8910 1.0170	0.9110 1.0340	0.9240 1.0410	0.9310 1.0690	0.9520 1.0820	0.9640 1.0900	0.9780 1.1180	0.9850 1.1470	0.9920	0.9556	03Q07P
0.8590 1.0060	0.8810 1.0360	0.9040 1.0540	0.9230 1.0490	0.9170 1.0540	0.9400 1.0830	0.9700 1.1220	0.9870 1.1260	0.9810 1.1310	0.9760	1.3084	03Q07Q

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TABLE I.21 (cont)

<u>1</u> <u>11</u>	<u>2</u> <u>12</u>	<u>3</u> <u>13</u>	<u>4</u> <u>14</u>	<u>5</u> <u>15</u>	<u>6</u> <u>16</u>	<u>7</u> <u>17</u>	<u>8</u> <u>18</u>	<u>9</u> <u>19</u>	<u>10</u>	<u>Q_M</u>	<u>ELEMENT</u>
0.9100 1.0210	0.9160 1.0410	0.9220 1.0800	0.9670 1.0690	0.9560 1.0590	0.9620 1.0780	0.9820 0.0000	1.0240 0.0000	1.0130 0.0000	1.0020	1.4346	03Q07R 6
0.8880 1.0190	0.8980 1.0440	0.9080 1.0360	0.9290 1.0480	0.9410 1.0460	0.9510 1.0710	0.9760 1.1010	0.9710 1.0990	0.9820 1.0980	0.9940	1.0477	03Q07S

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II. PHOEBUS-2 CALCULATIONS

All Phoebus-2 neutronic calculations were performed by using the S_n , multigroup, transport-theory codes developed at LASL. Since inception, these codes have been continually modified and improved. The one- and two-dimensional versions currently in use are called DTF-IV¹ and 2DF, respectively.

All calculations used the S_4 angular segmentation and the transport approximation. The one-dimensional cylindrical calculations approximated axial leakage by incorporating a fictitious "DB²" absorption cross section in each region. An effective delayed fraction of 0.0072 was used to convert calculated values of ($k_{eff}-1$) to units of dollars.

The multigroup microscopic cross sections have also undergone modifications and improvements during the past several years. The latest 25 energy-group cross sections used in the posttest analysis are presented in LA-4484-MS, (U) "Twenty-Five Group Cross Sections Used in the Los Alamos Rover Program." Although some calculations reported in the following sections may have employed older sets, unless stated otherwise, the results are believed to be consistent with the latest compilation.

The calculational effort may be divided into the three following broad categories.

- (1) Critical Experiment calculations.
- (2) Phoebus-2 ambient calculations.
- (3) Cold-to-hot calculations.

A. Critical Experiment Calculations

The critical experiments performed throughout the Phoebus program were checked with calculations whenever possible. Because the calculations generally agreed well with the measurements, they were used with a high degree of confidence to predict perturbations in both the reactor design and the critical mockups. It was also hoped that agreement with ambient experiments implied an ability to predict reactor behavior during operation. As will be explained in Sec. II.C, this premise, unfortunately, proved to be untrue.

1. **Honeycomb.** Calculations for the Honeycomb survey experiments described in Sec. I.A.1 are reported in detail in Ref. 2, therefore they are only briefly summarized in this report. Table II.1 shows calculated values of k_{eff} for the six critical assemblies described in Table I.1, along with some calculated and measured reactivity coefficients. As expected, the poorest agreement occurs in the niobium coefficients, which differ by as much as 30%.

TABLE II.1

CALCULATIONS OF HONEYCOMB ASSEMBLIES

Criticality:

Experiment	Nb Content, kg	K_{eff}
HC-1-1	0	1.015
HC-1-2	28	1.011
HC-1-3	55	1.012
HC-1-4	110	1.007
HC-1-5	220	1.002
HC-1-6	445	1.007

Reactivity Coefficients:

Experiment	Material	Reactivity, $\$/kg$	
		Calculated	Experimental
HC-1-1	Carbon	4.0	4.9
	Niobium	- 7.7	- 5.9
	Uranium	42	39
HC-1-6	Carbon	2.6	2.9
	Niobium	- 3.0	- 2.5
	Uranium	5.9	6.3

The one-dimensional calculational model for the uniformly loaded Phoebus-2 Honeycomb assembly (Sec. I.A.2) is shown in Table II.2, and the corresponding calculated results are given in Table II.3. Whereas the calculated values of k_{eff} , critical mass, and uranium worth agree well with the corresponding measurements, substantial differences exist in the material worths of carbon, niobium, and hydrogen. It should be noted that it is quite difficult to represent the heterogeneity and irregular geometry inherent in the Honeycomb assemblies in a simple calculational model.

2. **Zepo. a. Criticality.** Because the initial stacking of Phoebus-2 Zepo (Sec. I.B) was a relatively clean, well-defined experiment, it was used as a reference to check cross sections as they became available. The one-dimensional calculational model is shown in Table II.4. This model differs from the actual assembly in that it omits 838 kg of aluminum and 54 kg of stainless steel support structure located underneath the core (simulating inlet-end composition). The reactivity worth of this structure, measured to be +2.05\$, when added to the calculated axially bare excess reactivity of +0.45\$, gives a total reactivity of 2.50\$ compared to a measured value of 2.57\$.

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TABLE II.2
DIMENSIONS AND COMPOSITION
OF UNIFORMLY LOADED HONEYCOMB PHOEBUS-2 ASSEMBLY

	<u>Honeycomb No. 6</u>	<u>Honeycomb Ph-2</u>
Height, in.	52	52
Outer Radius, in.		
Core	27.5	27.5
Interface region	29.5	30.65
Reflector	36.0	38.15
Material Density (atoms/ 10^{-24} cm ³)		
Core		
²³⁵ U	2.167×10^{-4}	3.063×10^{-4}
²³⁸ U	1.59×10^{-5}	2.252×10^{-5}
Carbon	5.876×10^{-2}	5.876×10^{-2}
Niobium	1.424×10^{-3}	1.157×10^{-3}
Aluminum	3.704×10^{-3}	3.704×10^{-3}
Interface Region		
Carbon	7.28×10^{-2}	--
Aluminum	3.704×10^{-3}	3.617×10^{-2}
Reflector		
Beryllium	1.12×10^{-1}	1.12×10^{-1}
Aluminum	3.704×10^{-3}	3.704×10^{-3}

TABLE II.3
CALCULATIONS OF UNIFORMLY LOADED
HONEYCOMB PHOEBUS-2 ASSEMBLY

<u>Parameter</u>	<u>Calculated</u>	<u>Experiment</u>
K_{eff}	1.0091	1.00
Critical mass, kg U	243	260
Reactivity Coefficients, ρ/kg :		
Uranium	7.3	7.3
Carbon	2.4	3.0
Niobium	- 3.4	- 2.6
Aluminum	0.65	0.73
Hydrogen	362	470

Measured and calculated values of uniform core reactivity coefficients are shown in Table II.5. Agreement, in general, is considered good.

b. Fission Distribution. The radial fission distribution measured in the 90° sector of production fuel elements in Zepo was shown in Fig. 1.50 along with corresponding calculational results. In the one-dimensional calculation, the 18 control drums were simulated by a boron sheath, 0.10 in. thick, containing the same amount of boron as is actually present in the drums. The sheath was positioned in the reflector so that its reactivity effect was approximately the same as that observed for the drums. This one-dimensional representation must be considered a gross simplification of the true conditions existing in the reflector. It has been used primarily to approximate conditions for cold-to-hot change calculations, and not to predict fissions/g-U on an absolute basis. Nevertheless, it is of interest to compare the resultant calculated fission distribution with the corresponding measurements. The calculated fissions/g-U exhibit slightly less peaking at the core edge than the experimental points.

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TABLE II.4
CALCULATION MODEL FOR PHOEBUS-2 ZEPO

Region	Outer Radius, cm	Material	ρ g/cm ³	Atomic Density $\times 10^{24}$	Total Wt kg
Core Zone I	37.63	²³⁵ U	0.133	3.166×10^{-4}	78.09
		²³⁸ U		2.383×10^{-5}	
		Niobium	0.150	9.709×10^{-4}	88.0
		Carbon	1.13	5.669×10^{-2}	663.9
Core Zone II	63.21	²³⁵ U	0.1716	4.088×10^{-4}	183.68
		²³⁸ U		3.077×10^{-5}	
		Niobium	0.148	9.570×10^{-4}	158.0
		Carbon	1.11	5.574×10^{-2}	1189.3
Core Zone III	69.637	²³⁵ U	0.0908	2.163×10^{-4}	32.16
		²³⁸ U		1.628×10^{-5}	
		Niobium	0.143	9.283×10^{-4}	50.7
		Carbon	1.142	5.729×10^{-2}	404.6
Graphite Periphery	70.754	Carbon	1.632	8.187×10^{-2}	106.1
Interface Region	78.90	Aluminum	1.55	3.459×10^{-2}	783.5
Reflector	100.33	Beryllium	1.515	1.013×10^{-1}	2415

TABLE II.5
REACTIVITY COEFFICIENTS IN PHOEBUS-2 ZEPO

Material	Reactivity Coefficient, β /kg	
	Calculated	Measured
Uranium	+ 7.3	+ 7.7
Niobium (75-g tubes)	- 3.2	- 3.2
Carbon	+ 2.8	+ 2.8
Hydrogen	+375	+420
Molybdenum	- 7.1	- 9
Boron (natural)	-650	
Inconel 600	- 0.5	- 0.5
Inconel 718	- 1.0	- 0.9

c. Effect of Interface Hydrogen on Radial Fission Distribution. A series of measurements was performed in Zepo to provide checkpoints for calculating the effect of peripheral hydrogen on the radial fission distribution. Peripheral hydrogen was mocked up with polyethylene sheets covering a 90° arc in the interface and in the reflector regions. The hydrogen concentration approximated that expected during full-power operation.

The effect of peripheral hydrogen was investigated both with and without the presence of core hydrogen. The core hydrogen was mocked up with polyethylene strings as described in Sec. I.C.2. Because loading the entire core would have introduced an excessive amount of reactivity, the hydrogen was inserted in only a fraction of the core surrounding the radial fission traverse.

The experimental fission distribution was obtained by irradiating and counting 7½-in.-long U-Al wires centered about the core midplane. The corresponding calculations were performed in one-dimensional cylindrical geometry. Core hydrogen density was taken as that existing at the midplane where the irradiation took place.

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The experimental and calculated results are shown in Fig. 2.1. The effect of peripheral hydrogen was to increase fissions at the core edge by approximately 20% and appears to be independent of the presence of core hydrogen. The calculations are seen to be in excellent agreement with the measurements.

3. Kiva and Nevada Assemblies. The two-dimensional calculational model of the Phoebus-2 Kiva assembly is shown in Fig. 2.2. The model contains a total of 199 material zones, 117 of which are in the fueled core region. The reason for the great detail in the axial direction is not for ambient calculations, but for simulating operating conditions that exhibit significant axial variations in both core hydrogen and temperature. The atomic densities in each material zone are shown in Table II.6.

The initial calculation was run with no boron in the reflector and yielded a k_{eff} of 1.030 (4.17% excess reactivity). This calculation can be compared with measurements as follows: the Phoebus-2 Kiva assembly was critical at a control-rod setting of 111° (Sec. I.E). From the control-rod calibration curve (Fig. 1.62), we see that an additional 2.32% would result if the rods were rotated out from 111 to 180°. Assuming the rods at 180° reduce reactivity by 1.08%, and the W-Mo end caps that were present in the calculation, but not in the Kiva, are worth 0.12%, a total "experimental" excess reactivity of 3.52% is obtained. The two-dimensional calculation therefore

Fig. 2.1.

Computed and measured fission perturbation.

appears to give 0.65% more reactivity than the Kiva assembly.

The measured and calculated axially integrated radial fission distributions are compared in Fig. 2.3. The solid curve in the figure is the best fit obtained from the fuel-element counting data shown in Fig. 1.67. The calculated points marked "X" in Fig. 2.3 were obtained from the reactor model (incorporating the boron sheath) described in Table II.6. Those points marked "O" were obtained from a calculation that added 195 kg of carbon in the support block region (zone 195, Fig. 2.2) to more closely approximate the conditions under which the fuel-element irradiation was performed. Experimentally, it was necessary to add this amount of graphite to move the control rods in to 95°. The calculations, this time, show slightly greater peaking at the core edge.

The final criticality check in the Phoebus-2 program was with the two-dimensional model described in Fig. 2.4 and Table II.7. This model was used for the extensive posttest reactivity analysis described later. It is essentially the same as that used for the Kiva assembly calculations except for a simplification of the axial detail, the addition of 24 tantalum shim elements, and a slight remodeling of the seal-cavity region. These calculations used 2DF, the latest version of the transport theory code, along with the most recent 25-group cross sections presented in the Appendix.

The calculated reactivity of the ambient reactor with no boron was 1.0217 or +3.01%. This calculation can be compared to the NRDS assembly as follows. The NRDS assembly was critical at a control drum angle of 116° equivalent to a boron poisoning of 3.11%. To compare the calculated value of 3.01% with the NRDS observation, the following corrections for differences between the calculational model and the NRDS assembly must be applied.

Addition of nozzle	+ 0.33%
Addition of shield	+ 0.06
Addition of instrumentation	- 0.20
Core material changes	+ 0.13
Tantalum shim changes	+ 0.03

Net change between calculational model and NRDS assembly + 0.35%

The calculated excess reactivity of the NRDS assembly corrected for these differences is therefore + 3.36%, within 0.30% of experimental observation.

B. Phoebus-2 Ambient Calculations

The initial Phoebus-2 calculations were performed by Hedstrom and Charatz. These calculations indicated that the Phoebus-2 concept was indeed feasible from the neutronic point of view. In particular, they showed that sufficient control span was available with rotating drums

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Phoebus-2A Kiva assembly model.

Note-Dwg. not to scale.

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TABLE II.6
PHOEBUS-2-KIVA ASSEMBLY TWO-DIMENSIONAL, CALCULATIONAL MODEL

Zone	Atomic Density $\times 10^{24}$, atoms/cm ³											
	Oralloy	Carbon	Nb	Mo	Inconel 718	Ta	Fe	Ni	Al	B	Inconel 600	V
1-9	2.397E-4	6.107E-2	1.115E-3	4.118E-5	8.031E-4	7.115E-5						
10-18	2.544	6.109	1.115	3.950								
19-27	2.780	6.093	1.104	4.446								
28-36	3.097	6.083	1.143	4.569								
37-45	3.550	6.079	1.098	4.778								
46-54	4.083	6.035	1.135	4.941								
55-63	4.548	5.990	1.162	4.956								
64-72	4.779	5.973	1.174	4.859								
73-81	4.265	6.019	1.154	4.608								
82-90	3.599	6.079	1.107	5.035	8.433							
91-99	2.865	6.103	1.124	4.519								
100-108	2.121	6.128	1.130	4.215								
109-117	0.942	6.337	1.243	3.540	1.584E-3							
118-121		8.948	3.237E-5									
122-126		1.038E-1					2.746E-3	1.462E-3				
127-134		7.958E-2			2.00 E-4		7.822E-4	5.389E-4				
135		3.813										
136		0.953										
137		2.859										
138-140		1.430										
141-142		1.506										
143		1.344							3.41 E-2			
144		0.336										
145		1.008										
146-148		0.504										
149-150		0.672										
151-158									3.364E-2			
159-165										1.042E-1		
166-172										1.094E-1		
173											2.35 E-2	
174-180												
181												
182		1.060E-2			7.93 E-4				6.03 E-2			
183		1.350					3.29 E-3		4.11 E-3			
184		0.240					3.00					
185							4.30		1.90 E-3			
186					3.24 E-3		0.29		4.90 E-2			
187						- void -	3.30		1.90 E-2			
188												
189												
190												
191							7.42 E-3	5.52 E-2	4.09 E-2			
192									5.00 E-2			
193		6.06 E-2	2.13 E-3		7.93 E-4	- void -			5.60 E-2			
194		5.96	2.69 E-3									
195		1.69										
196				2.88 E-3	3.06 E-3	- void -						
197												
198												
199		6.0 E-2							3.40 E-2			
												3.90 E-3

in the reflector, fuel element loadings required for criticality were within an acceptable range, and radial fuel loading variation complemented by flow orificing could adequately flatten the exit gas temperature profile.

The reactor calculational model was kept current as the design progressed. The primary uses of this model were to guide proposed changes in the reactor design that might affect neutronics and to predict the cold-to-hot reactivity and fission distribution changes. As the program progressed, the reactor calculational model merged with the Kiva and NRDS models previously described. In the remainder of this section, we will discuss the neutronic characteristics of the ambient Phoebus-2 reactor as obtained from the transport-theory calculations. The cold-to-hot changes will be discussed in the following section.

Phoebus-2 must be classified as an intermediate-spectrum reactor with approximately 50% of the fissions initiated by neutrons between 1 eV and 1 keV. The core volume-average flux spectrum is shown in Fig. 2.5 and the

corresponding energy distribution of neutrons causing fissions is shown in Fig. 2.6. The median fission energy is seen to be 72 eV (50% of all fissions occur above that energy) with only 8% of the fissions being initiated by subcadmium (< 0.4 eV) neutrons.

Because the beryllium reflector moderates and returns a substantial number of neutrons to the core, the flux spectrum has a strong radial dependence, becoming softer at the core periphery. One manifestation of this radial flux variation is seen in the fissions/gram distribution (Fig. 1.67) that exhibits a sharp rise at the core edge. The effect of the moderating reflector can also be seen in Fig. 2.7, which gives the median fission energy as a function of core radius. At the core edge, 50% of the fissions are produced by neutrons below 1 eV.

A core neutron balance, normalized to 1 neutron boron, is shown in Table II.8. Note the importance of niobium that absorbs approximately 8% of all neutrons produced.

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Fig. 2.3.

Comparison of 2-D calculations with fuel element counting data.

C. Cold-to-Hot Calculations

As the reactor progresses from ambient to operating conditions, changes occur that affect both the reactivity and the radial fission distribution. These changes include (1) addition of propellant hydrogen and (2) changes of material temperatures in both core and reflector. It was the objective of the cold-to-hot calculations to predict the resulting changes in reactivity and fission distribution so that, by appropriate compensations, the reactor would operate at a prescribed control-drum position and with a relatively flat radial temperature distribution during the full-power hold. Based upon these calculations, the reactor was shimmed with tantalum support elements so that the control-drum position was expected to be $\sim 95^\circ$ at full power, and the fuel-element loadings were tailored so that the predicted changes in the radial power distribution would result in a flat temperature profile. A miscalculation of either effect (reactivity or power ratio) could produce an unwanted variation in the operating temperature distribution.

The pretest predictions of the cold-to-hot reactivity changes for the full-power hold are summarized in Table II.9. The one- and two-dimensional calculations incorporated a boron sheath in the reflector to simulate control drums at 95° (the expected hot-critical position). The fourth column in the table presents the final predictions based on the best available pretest data. Except for the peripheral hydrogen effect, the 1D and 2D calculations are in good agreement. The calculated 2D uniform hydrogen worth of 3.74\$/kg is approximately 10% less than

that given by the corresponding Kiva measurement. The final hydrogen worth prediction of +4.05\$/kg was essentially an average of experimental and calculated results. Note the large negative contribution of Doppler broadening in the resonance absorbers. The expected overall reactivity change between ambient and full power was +1.60\$.

The calculated hot or cold fission ratios for the full-power hold are shown in Fig. 2.8. Curves are drawn for the component effects of hydrogen addition, core and reflector temperature changes, and core expansion. Note that the resulting peak of $\sim 12\%$ at the core edge is made up of a sharply increasing function due to peripheral hydrogen and a decreasing function due to temperature changes.

It was in the area of cold-to-hot predictions that the Phoebus-2 reactor exhibited its major neutronic surprises. On May 22, 1968, the reactor attained initial criticality at NRDS at a control-drum angle of 116° . It was then taken through a series of five experimental plans (EPs) designed to investigate neutronic, thermal, structural, and material behavior under a variety of operating conditions. The results of these tests are reported in detail in Ref. 3.

The pertinent observations relating to neutronic behavior made during or shortly after the test are summarized.

(1) With all reactor temperatures at or near ambient, the initial delayed-critical drum position of 116° agreed very closely with the value predicted from the Kiva assembly measurements.

(2) The EP-1 and EP-2 measurements of hydrogen and temperature reactivity coefficients agreed (within experimental accuracy) with predicted values. The hydrogen reactivity coefficient was measured with gaseous hydrogen.

(3) With liquid hydrogen supplied as a coolant and the reactor operating at substantial power, the control-drum positions differed from prerin predictions by amounts equivalent to an apparent reactivity loss of 1.5 to 2.5\$.

(4) Although the control drums were substantially further out than predicted, the core radial temperature profile did not exhibit the edge fission peaking that would have been expected at the observed drum positions.

(5) Differential control-drum worth, when measured at ambient conditions, was in close agreement with the Kiva measurements. When measured at operating conditions, however, differential worths were significantly lower than the Kiva and ambient-condition values.

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Fig. 2.4.
Phoebe-2A postrun 2-D calculational model.

NOTE-Dwg. not to scale.

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TABLE II.7
PHOEBUS-2 POSTRUN, TWO-DIMENSIONAL CALCULATIONAL MODEL

Atomic Density x 10 ²⁴ atoms/cm ³										
Zone	Oralloy	Carbon	Nb	Mo	Inconel	Ta	Fe	Ni	Al	Be
1	0.2397E-3	0.6107E-1	0.1115E-2	0.4142E-4	0.8031E-3	0.7115E-4				
2	0.2544	0.6109	0.1115	0.3960		0.5808				
3	0.2780	0.6093	0.1104	0.4446		0.1016				
4	0.3097	0.6083	0.1143	0.4569		0.1016				
5	0.3550	0.6079	0.1098	0.4778		0.0610				
6	0.4083	0.6035	0.1135	0.4941						
7	0.4548	0.5990	0.1162	0.4956						
8	0.4779	0.5973	0.1174	0.4859						
9	0.4265	0.6019	0.1154	0.4608						
10	0.3599	0.6079	0.1107	0.5035						
11	0.2865	0.6103	0.1124	0.4519						
12	0.2121	0.6128	0.1130	0.4215						
13	0.0949	0.6337	0.1243	0.3540						
14		0.8948	0.3237E-3							
15		1.038								
16		0.7958								
17		0.1624								
18		0.0442								
19										
20										
21										
22										
23		0.106 E-1								
24		0.135 ↓								
25		0.024 ↓								
26										
27										
28										
29										
30										
31										
32										
33		0.606 E-1	0.213 E-2							
34		0.596 ↓	0.269 E-2							
35		0.169 ↓								
36										
37		0.60 E-2								
38										
39										
40										

0.4134E-1
0.3364
0.0137
0.0122
0.6030
0.0411

0.1049E+0
0.1094E+0

0.115E-1

0.190 E-2
0.490 E-1
0.150 E-1

0.409 E-1
0.500 E-1
0.560 E-3

0.2746E-2
0.7822E-3

0.1469E-2
0.5389E-3

0.329 E-2
0.330 E-1
0.430 E-2
0.290 E-3
0.333 E-2

0.742 E-2

0.550 E-1

0.340 E-2
0.138 E-1

0.61 E-2

0.793 E-3
0.793
2.74
0.793
0.324

VOID

0.350 E-3
VOID

0.793 E-3

0.306 E-2

0.650 E-2

VOID

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Fig. 2.5.
Phoebus-2 core average flux spectrum.

Fig. 2.6.
Energy distribution of neutrons producing fission.

Fig. 2.7.
Median fission lethargy as a function of core radius.

TABLE II.8

**PHOEBUS-2 CORE NEUTRON BALANCE
(per neutron born)**

Absorptions

U(23)	0.583
Niobium	0.077
Carbon	-
Inconel	0.015
Molybdenum	0.006
Tantalum	0.009
Total core absorptions	0.690

Leakage

Radial	0.177
Axial	0.133
Total leakage	0.310

D. Posttest Analysis

1. Reactivity Changes. An extensive analysis of the reactivity changes observed during the Phoebus-2 reactor test was performed as a joint effort within LASL's N Division. This study has been reported in detail in Ref. 4 and highlights pertaining to the neutronic calculations are summarized here. Reactor conditions were obtained for 47 steady-state holds occurring during experimental plans 3, 4, and 5 to provide information for the posttest reactivity analysis. The final reactivity discrepancies fell within $\pm 25\%$ except for a few cases where the quantity of hydrogen in the reflector was uncertain because of probable two-phase flow.

The control rods were withdrawn about 30° further during power operation than had been predicted before the run, resulting in some core edge fission and temperature peaking. The magnitude of this peaking, as indicated by the posttest fission measurements, is slightly less than the current predictions.

The posttest analysis differed from the pretest analysis in two primary respects (in addition to more realistic values of test conditions). First, new thermalization cross sections were used, in particular, cold molecular hydrogen cross sections. Second, hot and cold calculations were compared with control poison removed, bypassing (at least temporarily) model difficulties in representing the 18 discrete control rods for one- or two-dimensional (r,z) calculations. The resulting hot reactivity without control-rod poison can then be compared with an observed hot critical condition by making use of either computed or experimental indications of the reduction in control effectiveness.

Because the cold-to-hot calculation applies to the

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TABLE II.9
PRETEST COLD-TO-HOT REACTIVITY CHANGES FOR FULL-POWER HOLD

<u>H₂ Effect</u>	<u>1D Calculation^a</u>	<u>2D Calculation</u>	<u>Kiva Measurement</u>	<u>Final Prediction</u>
Core H ₂ (uniform)	3.86	3.74	4.15	
Core H ₂ effectiveness	0.796	0.788		
Core H ₂ worth	4.60	3.84	~ 4.25	4.05
Peripheral H ₂	0.52	0.15		{ 0.30
Inlet H ₂		0.09	0.06	
Total H ₂	4.52	4.08		+ 4.35
<u>Neutronic Temperature and Mo Loss</u>				
Beryllium thermal base	-0.29	-0.31		
Carbon thermal base	-0.08			
Uranium doppler	-0.86			
Niobium doppler	-1.24			
Tantalum doppler	-0.17			
Molybdenum loss ^a	+ 0.51			
Total neutronic and molybdenum loss	-2.13	-2.20		-2.20
<u>Expansion</u>	-0.64	-0.55		-0.55
<u>Overall</u>				+ 1.60\$

^a Assumes one-half of the molybdenum initially present is lost.

Fig. 2.8.

Computed hot-to-cold fission factors for Phoebus-2.

reactor without control poison, the experimental reactivity, $\rho(\text{EXP})$, is defined as the reactivity of the system with control poison removed. Thus, for a critical system (overall reactivity zero),

$$\rho(\text{EXP}) = \rho(\text{control rods}),$$

which is the reactivity gained when the control elements are removed. The corresponding difference of reactivity between an operating condition and the ambient reference condition is

$$\Delta\rho(\text{EXP}) = \rho(\text{control rods}) - \rho_0(\text{control rods}).$$

The reference ambient critical reactivity can be represented by

$$\rho_0(\text{control rods}) = 4.74 + 3.74 \cos 0.983(\theta + 3.2)$$

for $\theta > 90^\circ$, where the reactivity difference between 180° and complete removal is 1.0\$. It is assumed that the hot control rod response is identical to that for the cold reactor except for an effectiveness factor Z, so that

$$\Delta\rho(\text{EXP}) = [4.74 + 3.74 \cos 0.983(\theta + 3.2)] Z - 3.03$$

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where the 3.03\$ is the contribution of the control rods at 116° in the ambient reference case. The differential control-rod worths measured at operating conditions are compared with the Kiva control-rod curve in Fig. 2.9. The apparent Z-factor for the curve drawn is 0.66. Corresponding integral control-rod worths are given in Fig. 2.10.

Analytical reactivity change $\Delta\rho(\text{ANAL})$ is considered to be the calculated effect of temperature and propellant hydrogen plus the reactivity contribution due to loss of carbon and molybdenum during the run. Thus,

$$\Delta\rho(\text{DIFF}) = \Delta\rho(\text{EXP}) - \Delta\rho(\text{ANAL})$$

is a measure of the adequacy of cold-to-hot calculations.

The results of the analysis of 47 holds during EP 3, 4, and 5 are summarized in Table II.10. Reactor conditions are tabulated for each case as well as for the individual contributions to $\Delta\rho(\text{ANAL})$ and the experimental Z-factors used to obtain $\Delta\rho(\text{EXP})$. For some holds, the reactor was slightly supercritical or subcritical so that a few cents correction had to be made in the value of

Fig. 2.9.

Phoebus-2 differential control-rod worths.

Fig. 2.10.

Phoebus-2 integral control-rod worths.

$\Delta\rho(\text{EXP})$ obtained from the control-rod settings. This correction is listed in the table as $\rho(\text{total})$. Those holds for which H_2 density in the reflector is uncertain due to the probability of two-phase flow are marked with an asterisk. For all but one of the remaining cases, the value of $\Delta\rho(\text{DIFF})$ falls within $\pm 25\text{c}$.

Prerun calculations incorporated a boron sheath in the reflector to simulate control drums. The sheath was positioned in the cold reactor to reduce reactivity by the same amount as did the control rods at 95° (the expected operating position). The sheath was maintained at this fixed location throughout the subsequent cold-to-hot reactivity calculations. When the 47 holds listed in Table II.10 were computed by using prerun methods and cross sections, the value of $\rho(\text{DIFF})$ appeared to have almost a -2c bias.

The two-dimensional calculational model used in the posttest analysis has been described in Sec. II.A.3. The calculated cold-to-hot reactivity changes are discussed below.

a. Core-Temperature Reactivity. Overall core-temperature calculations were performed by making uniform changes in temperatures of core materials, resulting in the curves shown in Fig. 2.11. The support element coefficient (essentially the tantalum Doppler effect) was treated separately because at high power these elements were as much as 250°R hotter than fuel. The effective core temperature for each hold was obtained from the axial temperature distribution weighted by the square of the relative fissions.

b. Core-Hydrogen Reactivity. The reactivity effect of core hydrogen was separated into two terms, one for hydrogen in the fuel and the other for hydrogen in the tie tubes. In the calculations, hydrogen was distributed uniformly in the axial direction. An effective hydrogen weight was obtained from the axial density profile by using weighting factors obtained from a previous two-dimensional calculation of axial worth distribution. The resulting relationship between hydrogen content and reactivity is

$$\Delta k(\$) = \frac{92.81}{H_1 + H_2} (1.006H_1 + 0.967H_2) (1 - e^{-0.0168(H_1 + H_2)}),$$

where H_1 = weight of hydrogen in fuel, lbs, and H_2 = weight of hydrogen in tie tubes, lbs.

This formula was used for determining the core hydrogen reactivities in Table II.10.

c. Peripheral Hydrogen and Beryllium Temperature. The calculated reactivity change due to cold reflector conditions represents a significant departure from pretest predictions. The major change was the removal of the boron sheath from the calculational model and the

TABLE II.10

PHOEBUS-2 POSTTEST REACTIVITY DATA

EP	Power MW	Rod Position 0°	Δk Core H ₂ \$	Δk Core Temp	Δk Ref1 \$	Δk Carbon \$	Δk Mo \$	ρ (total) \$	Z Factor	$\Delta\rho$ (EXP)	$\Delta\rho$ (ANAL)	$\Delta\rho$ (DIFF)
3-2	1035	102.2	3.86	-1.30	-3.24	0.00	0.00	0.11	0.637	-0.47	-0.68	0.22
3-3	1197	102.1	3.79	-1.46	-3.08		0.00	0.04	0.638	-0.53	-0.76	0.23
3-4	1926	121.9	3.14	-2.33	-2.54		0.07	0.01	0.655	-1.25	-1.66	0.42
3-5*	461	119.3	2.12	-0.83	-1.82		0.07	-0.04	0.546	-1.52	-0.47	-1.05
4-1A*	317	126.1	2.48	-0.27	-1.74		0.07	-0.06	0.542	-1.74	-0.54	-2.28
4-1*	486	124.8	2.28	-0.92	-1.84		0.07	0.06	0.546	-1.58	-0.41	-1.18
4-2	1093	126.3	2.48	-1.85	-2.20		0.07	0.02	0.640	-1.43	-1.51	0.08
4-2A*	772	155.7	2.52	-1.28	-2.32		0.08	-0.06	0.589	-1.90	-1.01	-0.89
4-2B	968	135.3	2.42	-1.66	-2.34		0.10	0.06	0.638	-1.67	-1.49	-0.18
4-M1	1025	128.8	2.71	-1.59	-2.54		0.11	0.03	0.637	-1.50	-1.30	-0.20
4-M2	1149	135.6	2.54	-1.85	-2.44		0.14	0.04	0.642	-1.68	-1.62	-0.06
4-M3	1605	138.8	2.69	-2.16	-2.51		0.16	0.05	0.649	-1.75	-1.82	-0.07
4-M4	1716	133.5	2.90	-2.16	-2.63		0.18	0.04	0.651	-1.61	-1.71	-0.10
4-3	2194	149.9	2.63	-2.62	-2.19		0.23	0.05	0.660	-2.00	-1.96	-0.05
4-3A	2202	148.4	2.62	-2.63	-2.26		0.27	0.01	0.663	-2.00	-2.01	0.01
4-3B	2241	138.3	2.75	-2.62	-2.25		0.30	0.	0.663	-1.76	-1.82	0.06
4-4	2651	119.3	3.63	-2.57	-2.57		0.34	0.02	0.660	-1.13	-1.17	0.04
4-5	3627	137.9	3.18	-3.24	-1.95		0.45	0.	0.679	-1.72	-1.56	-0.16
4-6	4082	136.5	3.33	-3.39	-1.92	-0.04	0.50	0.01	0.683	-1.66	-1.52	-0.14
4-6A	3790	131.4	3.42	-3.20	-2.09	-0.07	0.54	-0.02	0.682	-1.53	-1.40	-0.13
4-6B	3523	138.8	3.08	-3.23	-1.95	-0.10	0.58	-0.01	0.682	-1.74	-1.62	-0.13
4-6C	4015	136.9	3.31	-3.36	-1.96	-0.12	0.60	0.	0.685	-1.68	-1.54	-0.14
4-6D	4018	131.3	3.43	-3.37	-1.94	-0.14	0.60	0.01	0.684	-1.50	-1.41	-0.09
4-7	3970	134.2	3.34	-3.33	-1.90	-0.24	0.64	0.	0.680	-1.61	-1.48	-0.13
4-8	3942	134.9	3.35	-3.31	-1.86	-0.42	0.67	0.	0.678	-1.63	-1.57	-0.07
4-9*	402	96.2	1.90	-0.71	-1.62			0.90	0.572	-1.51	-0.18	-1.33
5A-1*	517	128.4	2.16	-1.06	-1.87			0.02	0.520	-1.78	-0.52	-1.26
5A-1A*	521	127.4	2.15	-1.07	-1.96			0.	0.533	-1.74	-0.63	-1.11
5A-1B*	519	122.6	2.19	-1.06	-1.86			0.	0.572	-1.50	-0.49	-1.01
5A-1C	1040	127.7	2.41	-1.79	-2.24			0.04	0.637	-1.46	-1.38	-0.08
5A-1D	1107	122.0	2.74	-1.73	-2.30			0.06	0.638	-1.25	-1.04	-0.21
5A-2A	1279	126.6	2.58	-1.96	-2.22			0.02	0.643	-1.43	-1.36	-0.07
5A-2B	1275	118.7	2.75	-1.96	-2.24			0.01	0.642	-1.17	-1.21	0.04
5A-2	1277	125.9	2.58	-1.96	-2.22			0.	0.643	-1.42	-1.35	-0.07

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TABLE II.10 (cont.)

EP	Power MW	Rod Position 0°	Δk Core H ₂ \$	Δk Core Temp	Δk Refl \$	Δk Carbon \$	Δk Mo \$	ρ (total) \$	Z Factor	$\Delta\rho$ (EXP)	$\Delta\rho$ (ANAL)	$\Delta\rho$ (DIFF)
5A-2C	1202	122.1	2.65	-1.86	-2.19	-0.42	0.67	0.	0.641	-1.30	-1.16	-0.14
5B-1C	1000	127.0	2.46	-1.73	-2.19			0.04	0.638	-1.43	-1.20	-0.23
5B-1D	1089	120.9	2.77	-1.71	-2.34			0.03	0.638	-1.24	-1.04	-0.20
5B-2	1262	126.2	2.60	-1.96	-2.24			0.02	0.643	-1.41	-1.35	-0.06
5B-2A	1483	113.1	3.26	-1.91	-2.52			0.04	0.643	-0.93	-0.93	0.
5B-2B	1785	93.2	4.39	-1.87	-2.96			0.01	0.644	-0.17	-0.19	0.02
5B-3A	2006	127.6	2.95	-2.46	-2.24			0.	0.656	-1.45	-1.50	0.05
5B-3B	1998	122.2	3.12	-2.45	-2.22			0.	0.656	-1.27	-1.31	0.04
5B-3	2005	131.0	2.87	-2.46	-2.23			0.	0.656	-1.56	-1.58	0.02
5B-5	3432	138.2	3.31	-3.12	-1.89	-0.50		0.02	0.688	-1.69	-1.53	-0.16
5B-7	2812	162.6	2.47	-3.16	-1.56	-0.67		0.03	0.685	-2.27	-2.25	-0.02
5B-7A	2865	173.3	2.46	-3.20	-1.54	-0.92		0.	0.685	-2.32	-2.53	-0.20
5B-8	2037	139.2	2.82	-2.48	-1.94	-1.06		0.	0.662	-1.79	-2.00	0.21

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Fig. 2.11.

Core temperature reactivity changes.

use of new thermalization cross sections for beryllium and H_2 . These changes resulted in a more negative value for the reactivity change due to a cold reflector.

The prerun beryllium cross sections were prepared from crystalline scattering kernels generated by the SUMMIT code written at General Atomic.⁵ The only kernels available were for beryllium at 293 and 100°K. For the posttest analysis, cross sections were prepared by using a group of thermalization codes written by Clendenin⁶⁻⁸ at LASL. The beryllium cross-section sets, generated with the TOR⁶ and GLEN⁷ codes, were prepared for beryllium temperatures of 60, 100, 150, 200, and 293°K.

The prerun H_2 cross sections were for a room-temperature gas. The posttest H_2 cross sections were calculated by using the COL⁸ program, which essentially combines the functions of TOR and GLEN for molecular H_2 . Cross-section sets were generated for both ortho and para hydrogen at 293, 95, 60, and 45°K. In addition, the corresponding free-atom cross sections were obtained.

The calculated reactivity changes due to changes in reflector conditions are summarized in Figs. 2.12 and 2.13, which show the reactivity loss as a function of peripheral H_2 weight and beryllium temperature. These calculations assumed para hydrogen outside the core. Hydrogen temperatures were maintained constant at 350°R in the slit and cavity regions and at 108°R in the interface cylinder and reflector regions. It was found that variations in reflector H_2 temperature have only a small effect on reactivity; the maximum correction for temperatures differing from 108°R was 0.1\$.

Fig. 2.12.

Reflector reactivity changes as functions of H_2 content.

Fig. 2.13.

Reflector reactivity changes as functions of beryllium temperature.

To help clarify the mechanism causing the large reactivity loss in the cold reflector, computed neutron balances are compared in Table II.11 for two reactors—one with ambient beryllium and no outside H_2 and one with cold beryllium and cold outside H_2 . The reactivity decrease appears to be due to a significant increase in

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TABLE II.11
NEUTRON BALANCE FOR PHOEBUS-2

	Ambient Be No Outside H	180°R Be EP4-3B Outside H at 108°R	Difference
Reactivity	1.02637	1.00976	-0.0166 (-2.31\$)
Core absorptions	0.7096	0.6979	-0.0117
Peripheral absorptions			
Aluminum	0.0272	0.0382	+0.0110
Beryllium	0.0055	0.0109	+0.0054
Hydrogen	—	0.0073	+0.0073
Other	0.0035	0.0047	+0.0012
Total			+0.0249
Radial Leakage	0.1205	0.1110	-0.0095
Axial Leakage	0.1332	0.1298	-0.0034

Both cases contained EP-4-3B core hydrogen and were at a temperature of 2090°R.

absorptions in aluminum, beryllium and H₂ in the regions outside the core. There is no increase in leakage from the cold reflector. Apparently the lower neutron energies caused by thermalization in cold beryllium and H₂ cause neutrons to be absorbed in the reflector and interface regions before they can be returned to the core.

Reactivity changes calculated with para, ortho, and free gas H₂ are compared in Fig. 2.14. At a hydrogen temperature of 108°R, there is little difference in reactivity among the three models.

d. *Molybdenum and Carbon Loss.* Estimates based on post-mortem examination of Phoebus-2 fuel elements indicate that an amount of molybdenum equal to 0.67\$ and carbon equivalent to -1.02\$ in reactivity was lost from the reactor. Because the time dependence of these losses is unknown, they constitute, to a certain extent, free variables that can be used to smooth out residual discrepancies. They have been used for this purpose and at the same time trying to apply a criterion of physical reasonability to the curves of loss rate vs time. The net reactivity change has been matched to the between-EP ambient critical changes. In addition, the following general assumptions were made: (1) no carbon was lost during EP-3, the 7¢ increase in reactivity during this EP was attributed to molybdenum loss; (2) the remaining 60¢ of molybdenum loss took place during EP-4 along with 42¢ worth of carbon; and (3) the remaining 60¢ worth of carbon was lost during EP-5.

e. *Control-Drum Worth Factor.* The measured control-drum worth factor (Z) is plotted in Fig. 2.15

Fig. 2.14.

Reflector reactivity loss for free-gas, para and ortho hydrogen.

against beryllium temperature. Although the data scatter, there is some indication of a break in the curve near 100°R. This could be due to the effect of the Bragg cutoff in beryllium at low-neutron energies or due to the presence of two-phase H₂.

Fig. 2.15.

Control-rod worth factor vs beryllium temperature.

Fig. 2.16.

Measured and calculated hot-to-cold fission ratio.

Before a reactor test, experimental Z-factors are not available and it is necessary to rely completely upon calculations. An attempt was made to calculate Z for several operating conditions. In these calculations, the worth of a boron sheath, 0.1 in. thick, was computed in the ambient reactor and at several operating points. The ambient-sheath worth was 3.31\$, which is equivalent to the drum poisoning at 111°. In general, the calculated values are lower than those observed for the same reactor conditions. In Table II.12, the calculated Z factor and the resulting value of $\rho(\text{DIFF})$ are compared with experimentally deduced values for three holds.

2. Phoebus-2 Fission Distribution. Significant amounts of fissions were produced during three experimental plans (EP-3, EP-4, and EP-5) in the Phoebus-2 reactor test. The overall "whole element" fission distribution generated during these three EPs was measured by LASL Group J-11 using two-point gamma-ray spectroscopy data appropriately corrected for a radially dependent axial fission profile. The resulting hot fission distribution represents an average over a wide range of control-rod settings, hydrogen contents, and core and reflector temperatures. Nevertheless, it is of interest to compare this measured hot distribution to the predicted distribution expected during the EP-4 full-power hold.

This comparison is made by a hot-to-cold fission ratio shown in Fig. 2.16. The points in the figure are the

ratio of the hot distribution measured by LASL Group J-11 to the cold distribution measured by LASL Group N-2 in the Kiva assembly. This cold distribution is the result of a fuel-element irradiation at a control-rod setting of 95°, and subsequent counting of "whole element" gamma activity.

The curve of Fig. 2.16 is the ratio of the predicted hot distribution expected during EP-4-6C to the cold Kiva distribution. In addition to the calculated hot/cold fission ratio, the predicted curve in the figure incorporates several factors that account for changes that occurred between the Kiva irradiation and the Nevada assembly.

The Nevada assembly incorporated an extra 24 tantalum shim elements that were not present in the Kiva assembly. The calculated effect of these additional tantalum elements on the radial fission distribution gave corrections varying within $\pm 1\%$.

To bring the control rods in to 95° for the Kiva irradiation, it was necessary to add ~ 195 kg of graphite to the exit end of the core. The calculated effect of removing this additional graphite, which, of course, was not present in Nevada, was also small, $< 1\%$.

During the EP-4-6C hold, the observed control-rod position was 136.9°. The experimentally deduced effect on the radial fission distribution of moving the control

TABLE II.12

COMPARISON OF EXPERIMENTAL AND CALCULATED Z FACTORS

Hold	Z Factor		$\rho(\text{DIFF}), \%$	
	Experimental	Calculated	Experimental	Calculated
EP 3-4	0.655	0.520	+ 41.5	+ 4.9
EP 4-3b	0.663	0.547	+ 6.4	- 15.9
EP 5B-7	0.685	0.643	- 2.1	- 6.9

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rods from 95 to 136.9° (equivalent to 2.34\$) in the ambient reactor is given by Fig. 2.17.

The three factors so far presented correct the Kiva assembly measurement to the ambient Nevada assembly with the rods at 136.9°. It now remains to estimate the effect of changing from ambient to EP-4-6C operating conditions at a constant rod setting of 136.9°. This information, except for the effect of core expansion, has been obtained from the posttest neutronic analysis. Hot-to-cold fission factors were calculated both with and without a boron sheath present in the reflector. Figure 2.18 gives the results of these calculations, which include the effects of core hydrogen, core temperature, outside hydrogen, and cold beryllium. The reactivity worth of the sheath in the ambient calculation was -3.32\$, equivalent to the poisoning of the control drums at 111°. The corresponding ambient poisoning at 136.9° would be -1.98\$. By assuming a linear dependence of the hot-to-cold ratio on sheath poisoning, the calculated results for zero poisoning and 3.32\$ poisoning were interpolated to yield the hot-to-cold fission ratio corresponding to an ambient poisoning of 1.98\$ (drums at 136.9°). The final factor, the effect of core expansion was taken from previous calculations and is shown in Fig. 2.17.

The overall predicted hot-to-cold fission distribution for EP-4-6C shown in Fig. 2.16 is the combination of the five factors discussed. The resultant distribution is similar to the measured values obtained from LASL Group J-11, but shows somewhat more peaking toward the core periphery.

Fig. 2.18.

Hot-to-cold fission ratio for various control conditions.

Epilogue

The full-power test of the Phoebus-2 reactor took place on June 26, 1968. Because of excessive temperatures in the pressure vessel closure area, the reactor did not reach its design goal of 5000 MW and 4500°R, but was limited to a 13 min run at 4000 MW and 4000°R. Except for the specific problems of reactivity and pressure vessel closure overheating, performance was in good agreement with predictions.

The Phoebus-2 reactor tests provided information of considerable value to the nuclear rocket program even though all of the planned test objectives were not attained. The full-scale demonstration of the feasibility of regenerative cooling of the core support system, the achievement of high fuel element power density, and the demonstration that a reactor substantially larger than its predecessors could be built and operated near its design point in its first test are particularly important results. Even the spectacular failure of the reactor neutronics to match predictions has proved beneficial, providing valuable insight into hitherto unrecognized phenomena in the reactor neutron economy.

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Fig. 2.17.

Effect of drum motion and core expansion on fission distribution.

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