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Nuclear Materials & Propulsion Operation

710 MOCKUP NO. 1 CRITICAL EXPERIMENT

SUMMARY DATA REPORT

FL Sims
JF Kunze
GD Pincock
PL Chase

October 21, 1966

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October 21, 1966

Work performed at the Idaho Test Station
of the Nuclear Materials and Propulsion Operation ✓

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ABSTRACT

This report is a summary of the experiments associated with the three uniformly loaded core configurations related to the 710 Mockup 1 Critical Experiment Reactor. These configurations mocked up specific features of the then current 710 reactor experiment design. The experimental areas included initial loading, neutron lifetime, fission ratios, reflector control methods, reactivity coefficients and power distribution measurements. A major portion of the effort was applied to the latter two areas to determine the comparative effects between normally used fuel cells composed of rod-type materials and homogeneous fuel cells using fabricated fuel "compacts".

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TABLE OF CONTENTS

	<u>Page</u>
1.0	MOCKUP 1 CRITICAL EXPERIMENT CONFIGURATIONS 15
2.0	CONTROL ROD CALIBRATIONS 31
3.0	REACTIVITY COEFFICIENTS 40
3.1	Comparison of Compact and Rod Cells, and Core Heterogeneity Effects 40
4.0	NEUTRON LIFETIME MEASUREMENTS 54
4.1	Rossi-Alpha Measurements 54
4.2	1/v Poisoning to Determine the Prompt Neutron Lifetime 57
4.3	Boron Measurements of Low-Energy End of Core Spectrum 66
4.4	Comparison of Static 1/v-Poison and Rossi-Alpha Lifetime Results 66
5.0	FISSION RATIO MEASUREMENTS IN THE CORE 69
6.0	SPECTRAL SYNTHESIS FROM CADMIUM RATIO MEASUREMENTS IN THE REFLECTOR 72
7.0	POWER DISTRIBUTION MEASUREMENTS 79
7.1	Mockup 1A Power Distribution 79
7.1.1	Horizontal Radial Profile and Homogeneous Cell 83
7.1.2	Radial Profile at Table Separation Plane 83
7.1.3	Radial Profile Using Apex Cell 95
7.1.4	Summary and Comments Related to Mockup 1A Power Distribution Comparisons 99
7.2	Mockup 1C Power Distribution 112
7.2.1	Catcher Foil Measurements 112
7.2.2	Uranium-Aluminum Wire Measurements 123
7.2.3	Fission Probe Measurements 125

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~~CONFIDENTIAL~~

TABLE OF CONTENTS (Cont'd)

	<u>Page</u>
7.3 Mockup 1D Power Distribution	141
7.3.1 Longitudinal Power Distribution	141
7.3.2 Radial Power Distribution	146
7.3.3 Azimuthal Power Profile at Core Boundary	152
7.3.4 Power Distribution with Shield Next to Reflector	163
7.3.5 Summary of Mockup 1D Power Distribution	163
7.4 Summary and Conclusions Pertaining to Power Distribution Measurements	167

APPENDIX A

710 Critical Experiment Mockup 1B	170
Twelve Circular Module Mockup System	172
Ten Circular Module Mockup System	173
Summary and Conclusions of Mockup 1B	174
REFERENCES	200

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TABLE OF CONTENTS (Cont'd)

	<u>Page</u>
<u>FIGURES</u>	
1.1 Mockup 1 Core Layout for Three Reflector Thicknesses	16
1.2 Mockup 1 Horizontal Cross Section View	17
1.3 Cell Identification for Mockup 1 Core	18
1.4 Mockup 1A Cell Layout	21
1.5 Mockup 1C Cell Layout	22
1.6 Mockup 1D Cell Layout	23
1.7 Mockup 1 Core Loadings vs Reflector Thicknesses	27
1.8 Core and Reflector Dimensions - Mockup 1A	28
1.9 Mockup 1A Core Dimensions	29
2.1 Control Rod Configuration in Mockup 1A	32
2.2 Control Rod Configuration in Mockup 1C	33
2.3 Control Rod Configuration in Mockup 1D	34
2.4 Subcritical Rod Shape Curve - Mockup 1A (Movable Table)	35
2.5 Subcritical Rod Shape Curve - Mockup 1A (Fixed Table)	36
2.6 Shim Actuator Calibration - Mockup 1C	37
2.7 Shim Actuator Calibration - Mockup 1D	38
3.1 Measured Reactivity Worths - Oralloys Rods	43
3.2 Mockup 1C Measured Reactivity Worths of W and WO ₃ Rods	44
3.3 Mockup 1C Measured Reactivity Worth of Oxygen	45
3.4 Mockup 1D Measured Reactivity Worths of Tungsten Oxide and Tungsten	46
3.5 Mockup 1D Measured Reactivity Worth of Oxygen	47
3.6 Compact Fuel Segment	48
3.7 Comparison of Compact and Rod Type Cells, Reactivity Difference - Compact Minus Rod Cell	51

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

TABLE OF CONTENTS (Cont'd)

	<u>Page</u>
<u>FIGURES (Cont'd)</u>	
4.1 Mockup 1C B-10 Worth Measurement Locations	60
4.2 Mockup 1C B-10 Worth vs Radial Distance	61
4.3 Mockup 1C Normalized B-10 Worth vs Radial Distance	62
4.4 Mockup 1A and 1D B-10 Worth vs Radial Distance	63
6.1 Reflector Spectra From Cadmium Ratio Data	78
7.1 Mockup 1 Relative Radial Power Profile	81
7.2 710 Reactor Mockup 1A	82
7.3 Homogeneous Cell Placement	84
7.4 710 C.E. Mockup 1A Longitudinal Power Profile	86
7.5 710 C.E. Mockup 1A Relative Longitudinal Power Profile	87
7.6 710 C.E. Mockup 1A Composite Relative Radial Power Profile	88
7.7 710 C.E. Mockup 1A Relative Radial Power Profile - 13 cm from Reflected End of Core	89
7.8 710 C.E. Mockup 1A Relative Radial Power Profile - 36 cm from Reflected End of Core	90
7.9 Relative Radial Power Profiles Homogeneous Cell in 150 - 1, 7, 13 cm locations	91
7.10 Relative Radial Power Profiles Homogeneous Cell in 150 - 17, 26, 36 cm locations	92
7.11 710 C.E. Mockup 1A Relative Radial Profile	96
7.12 710 C.E. Mockup 1A Relative Radial Profile	97
7.13 Relative Radial Power Profiles Apex Cell in 263 - 1, 7, 13 cm locations	100
7.14 Relative Radial Power Profiles Apex Cell in 263 - 17, 26, 36 cm locations	101
7.15 Relative Radial Power Profiles Apex Cell in 563 - 1, 7, 13 cm locations	102
7.16 Relative Radial Power Profiles Apex Cell in 563 - 17, 26, 36 cm locations	103

~~CONFIDENTIAL~~

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TABLE OF CONTENTS (Cont'd)

	<u>Page</u>
<u>FIGURES (Cont'd)</u>	
7.17 710 C.E. Mockup 1A Relative Radial Power Profile-1 cm from Front Reflector	104
7.18 710 C.E. Mockup 1A Relative Radial Power Profile - 13 cm from Front Reflector	105
7.19 710 C.E. Mockup 1A Relative Radial Power Profile - 36 cm From Front Reflector	106
7.20 710 C.E. Mockup 1A Relative Radial Power Profile - Teflon Removed From Apex Cell and Buffer Zones	107
7.21 710 C.E. Mockup 1A Relative Radial Profile-Teflon Removed From Apex Cell and Buffer Zones	108
7.22 710 C.E. Mockup 1A Relative Radial Profile - Teflon Removed From Apex Cell and Buffer Zones	109
7.23 Relative Radial Power Profile Catcher Foil Tape Placed Between Table Halves Across Apex Cell	114
7.24 Longitudinal Power Profile - Run 483	115
7.25 Relative Radial Power Profile - In Total Core	116
7.26 Relative Radial Power Profile - In Total Core - Run 495	117
7.27 Sliced Compact Section and Simulated Homogeneous Cell	119
7.28 Sliced Compact Section and Simulated Apex Cell	120
7.29 Relative Radial Power Profile - Cell 150 - Run 510	121
7.30 Relative Radial Power Profile - Cell 163 - Run 518	122
7.31 Hole Identification Layout	124
7.32 Fuel Wire Data Longitudinal Power Profile - Run 502	126
7.33 Relative Radial Power Profile - Cell 150 - Run 486	127
7.34 Relative Radial Power Profile - Cell 150 - Run 502	128
7.35 Relative Radial Power Profile - Cell 163 - 13 cm From Reflected End of Core	129
7.36 Relative Radial Power Profile - Cell 150 - 13 cm From Reflected End of Core	130
7.37 U-Al Wire Counting Crystal	131
7.38 Mockup 1C Relative Isopower Profile Measured in Homogeneous Compact Cells (1 cm from reflected end of core)	132

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

TABLE OF CONTENTS (Cont'd)

	<u>Page</u>
<u>FIGURES (Cont'd)</u>	
7.39 Mockup 1C Relative Isopower Profile Measured in Homogeneous Compact Cells (10 cm from reflected end of core)	133
7.40 Fission Probe and Wire Comparison Longitudinal Data in Compact 163 - Hole 44	138
7.41 Fission Probe and Wire Comparison Longitudinal Data in Compact 163 - Hole 65	139
7.42 Fission Probe and Wire Comparison Longitudinal Data in Compact 163 - Hole 14	140
7.43 Longitudinal Power Profile-Average of Runs 599 and 645 Catcher Foil Data	143
7.44 Longitudinal Power Profile - Average of Runs 599 and 645 Catcher Foil Data	144
7.45 Longitudinal Power Profile - Average of Runs 599 and 645 Catcher Foil Data	145
7.46 Relative Radial Power Profile - Runn 599 Catcher Foil Data	147
7.47 Relative Radial Power Profile - Runn 599 Radial Across Apex Through Cell 163 Catcher Foil Data	148
7.48 Relative Radial Power Based on Integrated Longitudinal Average	149
7.49 Relative Radial Power Profile - Run 645 Catcher Foil Data Homogeneous Cell in 150	150
7.50 Relative Radial Power Profile - Run 645 Catcher Foil Data Apex Cell in 163	151
7.51 Relative Radial Power Profile - Run 645 Catcher Foil Data Rod Cell in 150	154
7.52 Relative Radial Power Profile - Run 645 Catcher Foil Data Rod Cell in 163	155
7.53 Relative Radial Power Profile Across Cell 150 (1 cm from reflected end of core)	156
7.54 Relative Radial Power Profile Across Cell 150 (7 cm from reflected end of core)	157
7.55 Relative Radial Power Profile Across Cell 150 (13 cm from reflected end of core)	158
7.56 Relative Isopower Plot Derived from U-Al Wires (1 centimeter from reflected end of core)	159

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

TABLE OF CONTENTS (Cont'd)

	<u>Page</u>
<u>FIGURES (Cont'd)</u>	
7.57 Relative Isopower Plot Derived From U-Al Wires (7 centimeters from reflected end of core)	160
7.58 Relative Isopower Plot Derived From U-Al Wires (13 centimeters from reflected end of core)	161
7.59 Mockup 1D Relative Isopower Profile Measured in Rod Type Cells (10 cm from reflected end of core)	162
7.60 Longitudinal Power Profile - Run 674 Catcher Foil Data	164
7.61 Relative Radial Power Profile - Run 674 Catcher Foil Data	166
7.62 Power Distribution Variations as a Function of Beryllium Reflector Thickness	169
A-1 Zonal Locations	185
A-2 Twelve Poison Segments in a Complete Reflector System	186
A-3 Poison Segment Rotational Positions in the Complete Reflector System - 710 C.E. Mockup 1B	187
A-4 Poison Segment Integrated Worth vs Angular Position	188
A-5 Circumferential Catcher Foil Profile in the Complete Reflector System	189
A-6 Reflector Configuration for the 12 Circular Module Mockup System	190
A-7 Poison Segment Rotational Positions in the 12 Circular Module Mockup System	191
A-8 710 C.E. Mockup 1B Poison Segment Integrated Worth vs Angular Position	192
A-9 710 C.E. Mockup 1B Circumferential Catcher Foil Profile 12 Circular Module Mockup System	193
A-10 710 C.E. Mockup 1B Circumferential Catcher Foil Profile 12 Circular Module Mockup System	194
A-11 710 C.E. Mockup 1B with Equivalent Safeties Removed	195
A-12 Reflector Configuration for the 10 Circular Module Mockup System	196
A-13 Poison Segment Rotational Positions in the 10 Circular Module Mockup System	197

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

TABLE OF CONTENTS (Cont'd)

Page

FIGURES (Cont'd)

A-14	710 C.E. Mockup 1B Poison Segment Integrated Worth vs Angular Position	198
A-15	710 C.E. Mockup 1B Circumferential Catcher Foil Profile in the 10 Circular Module Mockup System	199

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

TABLE OF CONTENTS (Cont'd)

Page

TABLES

1.1	Core Materials for Mockup 1 Critical Experiment	19
1.2	Mockup 1 Typical Fuel Elements	24
1.3	Comparison of Uniformly Loaded Mockup 1 Core Configurations	25
1.4	Interpolated 60% UO_2 , 40% W Mixture for $k\text{-eff} = 1.000$	26
2.1	Control Bar Worths	39
3.1	Core Material Worths - Mockup 1 Configurations	41
3.2	Mockup 1C Rod Cell Material Worths	49
3.3	Compact vs Rod Cell Based on Equivalent Masses	50
4.1	Rossi-Alpha Decay Components at Delayed Critical	55
4.2	Rossi-Alpha Neutron Lifetime Summary	58
4.3	Boron-10 $1/v$ Absorber Reactivity Coefficients	59
4.4	$1/v$ -Lifetime Measurements in Mockup 1	65
4.5	Contribution of Component Lifetimes to $1/v$ Effective Lifetime	68
5.1	Fission Rate Ratios Per Atom	71
6.1	Cadmium Ratios in the Reflector of Mockup 1 Configurations	75
6.2	Group Structure and Cross Sections for Spectral Synthesis	76
6.3	Spectrum in Region of 0.6 ev to 17 Kev, Fit to $\Phi(E) = \Phi_0/E^x$	77
7.1	Power Distribution Summary (typical values)	80
7.2	Homogeneous Cell Composition	85
7.3	Power Distribution Comparison	93
7.4	Apex Cell Composition	98
7.5	Mockup 1A - Ratio of Peak to End-of-Core Longitudinal Power	111

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

TABLE OF CONTENTS (Cont'd)

	<u>Page</u>
<u>TABLES (Cont'd)</u>	
7.6	Mass Equivalences in Various Cells 118
7.7	Mockup 1C Ratio of Peak to End of Core Longitudinal Power 134
7.8	Fission Probe Specifications 136
7.9	Fission Probe and Wire Comparison 137
7.10	Cell Loading Comparisons 142
7.11	Ratio of Peak to End of Core Longitudinal Power in Mockup 1D 153
7.12	Longitudinal Power Trends with Shield 165
7.13	Power Distribution Trends in Mockup 1D 165
A-1	Normalized Catcher Foil Data for Specific Power 175
A-2	Normalized Catcher Foil Data for Internal Typical Cells 176
A-3	Typical Cell Average Relative Specific Power Data 177
A-4	Typical Cell Relative Power Density Data 178
A-5	Relative Specific Power Data of Core Edge Typical Cells 179
A-6	Normalized Activity Comparison in the Complete Reflector System with Poison Segments at 0° and 80° 180
A-7	Normalized Activity Comparison in the 12 Circular Module Mockup System with Poison Segments at 0° and 80° 181
A-8	Characteristics of the Mockup 1B Configuration with a Zonal Loaded Core Containing 208.3 kg of Orallo Metal 182
A-9	Power Spike at Core Reflector Interface Relative to Center Cell of Core 183
A-10	Power Scallop Due to Control Drums 184

~~CONFIDENTIAL~~

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1.0 MOCKUP 1 CRITICAL EXPERIMENT CONFIGURATIONS

Following the completion of the 710 Basic Critical Experiment (1), (2), the experimental matrix was redesigned so as to accommodate a configuration, designated the Mockup 1, that more accurately mocked up engineering details of a power test reactor. The basic differences between the two configurations are that the Mockup 1 contained a core-shell and gap between the shell and core. The core had 2.3 times the volume of the core in the basic critical experiment.

The Mockup 1 reactor was designed with a circular core pressure vessel containing the 109 hex-shaped cell core structure. The portions internal to the core shell were constructed so as to mock up a test reactor design, with fuel element spacing of 1.497 inches in the across-flats dimension. The active fuel portion was 14.76 inches in length, and the equivalent circular diameter of the 109 fuel elements was 16.43 inches.

The core was supported within a 0.125 inch thick stainless steel cylindrical shell, with an outside diameter of 19.25 inches. This shell was supported within the normal aluminum hex matrix structure of the critical experiment split-table assembly. The supporting blocks were aluminum. A beryllium reflector consisted of nominally 85% Be*, 6.9% Al (the 0.031-inch thick hex-matrix structure, 1.758 inches across flats), and the remainder void. The equivalent inner diameter of this beryllium reflector was 19.80 inches. A drawing of the reactor configuration is shown in Figures 1.1, 1.2 and 1.3. The three basic uniformly-loaded core configurations were designated the Mockups 1A, 1C and 1D. These had equivalent beryllium (per the above specifications) reflector thicknesses of 7.43, 1.67 and 4.11 inches, respectively. A zonal loaded core designated the Mockup 1B was also assembled, with a reflector thickness of 7.43 inches. This latter configuration is briefly described and summarized in the Appendix.

The core was assembled of materials in the shape of rods and wires. The forms and masses of these are listed in Table 1.1.

The three reactor configurations discussed in the main body of this report were assembled in a uniformly loaded pattern until the loading was completed or criticality had been reached, at which time the core

-
- (1) J. F. Kunze and F. L. Sims, "710 Basic Critical Experiment Summary Data Report," GE-NMPO, GEMP-376, September, 1965.
 - (2) W. B. Henderson, H. L. Bermanis, J. E. MacDonald, and A. Prince, "710 Basic Critical Experiment Correlation," GE-NMPO, GEMP-377, September, 1965.

* Within the 1.758 inch across flats hexes, the average full hex beryllium bar gives 0.881 volume fraction, half hexes 0.851 and safety-bars 0.807, based on normal beryllium density of 1.85 gm/cc. The actual location of the control bars within the reflector are shown in Figures 2.1 through 2.3.

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CONFIDENTIAL
-16-

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Figure 1.2

MOCKUP 1 HORIZONTAL CROSS SECTION VIEW

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Figure 1.3

Core Layout
Facing Movable Table

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-18-

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TABLE 1.1

CORE MATERIALS FOR MOCKUP 1 CRITICAL EXPERIMENT

Core Length = 14.76 inches

<u>Material Form</u>	<u>Unit Mass per Core Length</u>
Hex-shaped canister, 1.5 inches across flats 90% Ta, 10% W, 0.01 inch thick	220.8 gm
"Oralloy" rods, 0.17 inch diameter 93.2% U-235 metal (5.4% U-238, 1.0% U-234, 0.4% U-236)	102.25 gm
W rods, 0.18 inch diameter	119.39 gm
WO ₃ rods, 0.18 inch diameter	42.35 gm
Ta rods, 0.156 inch diameter	77.59 gm
Ta wires, 0.060 inch diameter	11.56 gm
Al tubing, 0.1875 inch diameter	10.73 gm

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loading was adjusted by exchanging fuel and other materials to achieve the desired criticality. The Mockup 1A reactor was loaded using inverse multiplication methods, but the other two configurations were obtained incrementally by re-assembling each cell from a previously loaded configuration, with the reactor being maintained at an essentially critical condition.

The Mockup 1A core loading arrangement within each element is as shown in Figure 1.4. The equivalent reflector thickness was 18.8 cm. This uniformly loaded configuration was subcritical by 0.66% Δk .

The Mockup 1C consisted essentially of a uniformly loaded, single-hex-bar-thick (approximately 4.2 cm), beryllium-reflected core. Except for a few fuel elements near the center of the core used for adjusting k -excess, the loading was uniform, as shown in Table 1.2. Each fuel element was assembled according to Figure 1.5. The completely uniformly loaded configuration would have been supercritical by 1.335% Δk .

The Mockup 1D required the addition of a 1.5 hex thick reflector compared to Mockup 1C and a reduction in core fuel loading to compensate for the increased reflector thickness. As nearly as possible, the 60% UO_2 - 40% W relationship was maintained. The equivalent reflector thickness was approximately 10.4 cm. The volume-averaged reflector composition was 86.8% Be, 6.9% Al and 6.3% void. The uniformly loaded configuration was supercritical by 0.126% Δk .

The layout of this material in a single Mockup 1D fuel element is shown in Figure 1.6. This loading arrangement gave the required amount of uranium and tungsten for a 60/40 volume fraction mixture of UO_2 to W, but there was a 4.5% deficiency in oxygen.

A list of all core material weights, reflector thicknesses and uniformly loaded hex for each of the three Mockup 1 cores is given in Table 1.3.

The reference fuel element matrix composition consists of 60% UO_2 (10.9 gm/cc) and 40% W (19.3 gm/cc) by volume. The reactivity coefficients of the U, W and WO_3 were measured, nominally core-averaged, and the experimental loading was adjusted calculationaly to achieve the uniform relative loadings listed in Table 1.4 for three different reflector thicknesses, and an extrapolated value for no reflector. Figure 1.7 shows a curve of uniformly loaded 60-40 fuel element material vs beryllium reflector thickness for a critical reactor. Note, that the tantalum matrix structure has been maintained constant and the reflector material is nominally 87% Be and 6.9% Al in these idealized configurations.

Because of the mass of the core materials (2/3 of a ton) resting within the aluminum matrix, a slight distortion from perfect symmetry was present in the geometry of the system. Figures 1.8 and 1.9 show actual dimensions measured on the Mockup 1A configuration core and

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Figure 1.4

MOCKUP 1A CELL LAYOUT

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Figure 1.5

MOCKUP 1C CELL LAYOUT

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Figure 1.6

MOCKUP 1D CELL LAYOUT

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TABLE 1.2

MOCKUP 1 TYPICAL FUEL ELEMENTS

<u>Material</u>	<u>Number Rods or Wires</u>			<u>Rod Diameter (inch)</u>	<u>Weight/Rod (grams)</u>
	<u>1A</u>	<u>1C</u>	<u>1D</u>		
U	17	20	18	0.170	102.25
W	11	15	13	0.180	119.36
WO ₃	25	26	27	0.180	42.35
Ta-Rod	3	--	3	0.156	77.59
Ta Wire	--	26	4	0.040	11.56
Al Tubes	5	--	--	0.1875	10.73

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TABLE 1.3

COMPARISON OF UNIFORMLY LOADED MOCKUP 1 CORE CONFIGURATIONS

109 Cells, Volume = 51.298 liters

<u>Configuration</u>	<u>1A</u>	<u>1D</u>	<u>1C</u>
Reflector Thickness (cm) ⁽²⁾	18.9	10.4	4.2
Oralloy Weight ⁽¹⁾	189,414	200,614	222,905
Oxygen Weight	23,868	25,810	24,854
Tungsten Weight (rods)	234,680	267,988	290,348
Tantalum Weight (rods and wires)	25,372	30,400	32,710
Tungsten Weight (matrix)	2,405	2,405	2,405
Tantalum Weight (matrix)	21,645	21,645	21,645
Aluminum Tubing	5,598	0	0
Kex (%Δk) of uniformly loaded configuration	-0.66	+0.126	+1.335

- (1) All weights in grams. Values are for uniform loading. Weights include all the material weights in the active core, including, as shown, the matrix structure of 2405 gm W, 21645 gm Ta.
- (2) Reflector is nominally 87% Be, 7% Al, 8% void, averaged over the volume of the reflector. The actual location of the safety bars with a 0.807 effective volume fraction are shown in Figures 2.1 to 2.3.

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TABLE 1.4

INTERPOLATED 60% UO_2 , 40% W MIXTURE FOR $K_{\text{eff}} = 1.000$ (*)

<u>Configuration</u>	<u>1A</u>	<u>1D</u>	<u>1C</u>	<u>No Reflector</u>
Reflector Thickness (cm)	18,9	10.4	4.2	0
Oralloy Weight	192,770	200,490	214,982	233,728
Tungsten Weight (rods)	257,650	267,400	286,600	311,658
Tungsten Weight (matrix)	2,405	2,405	2,405	2,405
Oxygen Weight	26,230	27,230	29,185	31,783
Tantalum Weight (rods and wires)	32,710	32,710	32,710	32,710
Tantalum Weight (matrix)	21,645	21,645	21,645	21,645

All masses are grams in the active core.

(See Figure 1.9 Core length = 37.5 cm)

(*) Core materials are corrected to give 60% UO_2 -40% W by volume in the fuel elements, exclusive of the support matrix. UO_2 reference density of 10.9 gm/cc was adopted.

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27

CONFIDENTIAL

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-29-

Figure 1.9
MOCKUP 1A CORE DIMENSIONS

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reflector. The skewness of the cores of the other configurations should be identical, and the reflector skewness for the smaller reflector thicknesses should be proportional.

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2.0 CONTROL ROD CALIBRATIONS

The control rod configurations in the Mockup 1A, 1C and 1D reactors are shown in Figures 2.1, 2.2 and 2.3, respectively. The shim rod shape curves were measured by the usual bump period and/or by inverse multiplication (subcritical reactor) methods, giving the integral shape curves shown in Figures 2.4 to 2.7. The total safety system worth was determined by cross calibration with respect to the shim rods, assuming the same rod shape curves as for the shims, and/or by rod drop methods ⁽³⁾ using the finite (10 second) and infinite integral counting methods. A summary of the total worths of the shim and safety bars on these three reactors is given in Table 2.1.

Also included in Figure 2.7, for the Mockup 1D, is a plot of the calibration curve for the same shim rod with the reactor radially shielded by a single hex layer of stainless steel backed by a one-hex layer of borated epoxy. It will be noticed that the total shim worth was reduced by 13%.

In general, the control rod shape curves become more linear as the reflector becomes thicker. The trend is from the normal S-shaped curve (over the full reactor length), as for the thinly reflected 1C reactor, to a nearly straight-line curve as in the heavily reflected 1A reactor. In the 1A reactor, the curve is quite linear except near the reflected end where the differential curve appears to reach a slight maximum. The same general trend is observed with the addition of a shield, as can be seen in Figure 2.7. The rod shape curve becomes more linear when the shield is added.

The total rod worth for a given configuration of rods is less in a thickly reflected configuration. This effect is readily seen in Table 2.1 where the addition of a shield reduced the rod worth 13%. The safety system worths were also greater in the thinly reflected configurations. For instance, the three full-length actuators in the Mockups 1A and 1D just barely exceeded the required $2\% \Delta k$, while the equivalent actuator placement in the Mockup 1C resulted in nominally 15% greater safety system worth.

-
- (3) Feiner, F and Klann, P. G., "Methods of Calibrating Control Rods," in "Naval Reactors Handbook," Volume III, Page 6, "The Physics of Intermediate Spectrum Reactors," J. R. Stehn, ed. Naval Reactors Division of Reactor Development, United States Atomic Energy Commission, U. S. Government Printing Office.

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Figure 2.1
CONTROL ROD CONFIGURATION
IN
MOCKUP 1A

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Figure 2.2

CONTROL ROD CONFIGURATION
IN
MOCKUP IC

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Figure 2.3
CONTROL ROD CONFIGURATION
IN
MOCKUP 1D

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Fraction of Total Worth Inserted

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-36-

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CONFIDENTIAL
-37-
Shim Worth - %Ak

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-38-

Shim Worth - %Δk

Figure 2.7
SHIM ACTUATOR CALIBRATION - MOCKUP 1D
Shim No. 4
Unreflected End - 8.76-inch Active Fuel Length
Shim extension in reflected table fully inserted

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TABLE 2.1

CONTROL BAR WORTHS ($\% \Delta k$)

	<u>Worth (± 0.01)</u>
1. <u>Shim Bars</u>	
Mockup 1A	
4-bars, in-line, full length (1)	0.61 $\pm$ 0.04
unreflected end (1)	0.30 $\pm$ 0.02
reflected end (1)	0.31 $\pm$ 0.02
Mockup 1C - 3 bars, in-line, unreflected end	0.33
Mockup 1D - 4 bars, unreflected end	0.328
Mockup 1D - 4 bars, unreflected end with steel and epoxy shield	0.287
2. <u>Safety System - Full Length</u>	<u>Worth (± 0.1)</u>
Mockup 1A - four 5-bar groups	2.7 (2)
Mockup 1C - two 5-bar, one 4-bar groups	2.24 (2), (3)
Mockup 1D - three 5-bar groups	2.0 (2), 2.04 (3)

NOTE: Total travel distance of the shim rods is nominally 12 inches in each table, and for the safety rods - 15 inches. The outer three inch difference is worth an insignificant ($\sim 5\%$ fraction of the total worth).

- (1) The worths varied between shims on the top and bottom of the core, by the values shown, due to the eccentricity of the core in the core shell.
- (2) By cross calibration with shims.
- (3) By rod drop.

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3.0 REACTIVITY COEFFICIENTS

Some reactivity measurements were made with each core configuration to determine the worths of major core constituents. The results of these measurements, which are core length perturbations, are presented in Table 3.1. (Boron reactivity coefficients are presented in Section 4.2, $1/v$ -lifetime). Sufficient points were available to plot the worth of Orallo, tungsten, tungsten oxide and oxygen as a function of core radius for configurations 1C and 1D, and for Orallo on Configuration 1A. These data are presented in Figures 3.1 to 3.5 and in Table 3.1. Oxygen worth was calculated from the tungsten oxide worths. Unless otherwise specified, all worths were measured by inserting or removing core length rods into voids in the core structure.

It will be noted from Table 3.1 that there is a small increase in core average fuel worth as the reflector thickness increases, as would be expected since the core average spectrum would soften with the thicker reflector, and the fuel worth per unit mass increases as the total fuel loading decreases. Figure 3.1 shows that the fuel at the core edge decreases in worth with the thinner reflector of the Mockup 1C compared to Mockup 1D. The opposite effect occurs at the center of the core. This shift in fuel worth between these two configurations is essentially similar to the shift in the radial power profiles.

The worths of tungsten and tungsten oxide show very different values as a function of core radius between Mockups 1C and 1D. Although the points are few, there are sufficient to show that, as the core boundary is approached, sharp changes occur. In the harder spectrum at the core boundary of Mockup 1C, both tungsten and oxygen worths increase compared to the values near the center of the core. In the Mockup 1D, the WO_3 , W and oxygen worths were generally monotonically decreasing functions of core radius, as is usually expected.

3.1 Comparison of Compact and Rod Cells, and Core Heterogeneity Effects

To measure the relative differences between the specially manufactured fuel element compact cells and the normal rod type cells, the entire reactor was uniformly loaded to the approximate composition of the compact cells, resulting in the Mockup 1C configuration. When the compact elements were received, they were carefully weighed and compared with pre-shipment weights. A layout of the compact cell is shown in Figure 3.6.

Each compact cell consisted of several short segments. It took 10 to 11 segments for a 6-inch long fuel element and 15 to 16 segments for a 8.76-inch long fuel element. On the average, a full length

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TABLE 3.1

CORE MATERIAL WORTHS - MOCKUP 1 CONFIGURATIONS

Core Length Samples

<u>Material</u>	<u>Location</u>	Material Worths ($\% \Delta k / \text{gm} \times 10^3$)		
		<u>1A</u>	<u>1D</u>	<u>1C</u>
Uranium	Core Center	0.498	0.548	0.624
	Core Average (1)	0.323	0.303	0.294
	X30	0.320	0.380	0.192
	X40	0.233	0.263	---
	X50	0.173	0.186	0.137
	X51	---	---	0.183
	X62	---	0.163	0.112
	X63	---	---	0.119
	Edge (1-mil sheet)	0.611	---	---
Tungsten	Center 7	.00251	.00385	.00209
	Core Average (1)		.00335	.0213
	X30			.0189
	X40			
	X50			.0276
	X51		.0027	.0297
	X62 (2)	.00302	.00302	.0239
	X63 (2)		.00302	.0239
Oxygen (3)	Center 7	.202	0.236	0.204
	Core Average (1)		0.165	0.248
	X30		0.250 (4)	0.263
	X40		0.181 (4)	
	X50		0.096 (4)	0.262
	X51		0.126	0.276
	X62		0.0764	0.152
	X63		0.0764	0.246

- (1) Core averages do not include any sharp deviations occurring at the outer boundary of the core.
(2) Positions X62 and X63 measured together.
(3) Calculated from worth of W and WO₃ rods.
(4) Calculated from WO₃ values and W values from curve of W worth.

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(14.76") compact fuel element weighted 5155.80 ± 5.40 grams. Of this total weight, 46% was UO_2 and 54% was tungsten. The UO_2 consisted of 12.0% oxygen and 88.0% enriched (93.15%) uranium. The above values result in the following material weights per full length fuel element:

<u>Material</u>	<u>Weight (grams)</u>
U (enriched)	2087.1
O	284.6
W	2784.1

The rod type cell of the Mockup 1C configuration consisted of the following rod materials:

<u>Material</u>	<u>No. Rods</u>	<u>Weight/Rod (grams)</u>	<u>Total Weight (grams)</u>
Oralloy	20	102.25	2045.0
W	15	119.36	1790.4
WO_3	26	42.36	228.0 oxygen 873.4 tungsten

Comparing the two types of fuel elements, it will be noted that there is a deficiency of 42.1 grams of uranium, 120.3 grams of tungsten and 56.6 grams of oxygen in the rod type element.

Reactivity measurements were made to determine the worth of the three types of rods used in the rod type fuel element as a function of core radius. These results are given in Table 3.2. These values are presented graphically in Figures 3.1 and 3.2. From the measured worth of W and WO_3 rods, it was possible to calculate the reactivity worth of oxygen across the core radius. The results of these calculations are shown in Figure 3.3.

In addition to the above measurements, the reactivity difference between compact and rod type cell was measured at six positions across the core as shown in Table 3.3. Since the reactivity worths of the rod cell constituents were known and the mass difference between the compact and rod type cell was also known, it was a simple calculation to correct the rod cell for the mass deficiency and thus compare the two types of fuel elements on an equivalent mass basis. This was done and the results are given in Table 3.3. It will be observed here that the compact cell is worth less than the rod cell in every case. This comparison is also shown in Figure 3.7. Based on the curve shown in Figure 3.7, the differences

* The worth of fuel at the outside edge of the core was determined with 0.001-inch thick fuel sheet, which perturbs a thermal flux by approximately 12%.

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Figure 3.2
MOCKUP IC
MEASURED REACTIVITY WORTHS
W and WO₃ RODS

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Figure 3.3
MOCKUP 1C

MEASURED REACTIVITY WORTH OF OXYGEN
Calculated Based on Worth of W and WO₃

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-45-

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48-

(optional dimension)

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Figure 3.6
Compact Fuel Segment

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TABLE 3.2

MOCKUP 1C ROD CELL MATERIAL
WORTHS

Position	Material Worth % Δk			
	W (119.4 gm) Worth/Rod	33.6 gm W WO ₃ (8.7 gm O) Worth/Rod	U (102.2 gm) Worth/Rod	Oxygen Worth/gm
0			0.0638±0.0009	
Center 7	0.000250±0.000007	0.00186±0.00013		0.204x10 ⁻³
X30	0.00225±0.00035	0.00295±0.00028	0.0392±0.0001	0.263x10 ⁻³
X50	0.00330 *	0.00323 *	0.0140±0.0004	0.262x10 ⁻³
X51	0.00355±0.00028	0.00342±0.00024	0.0183±0.0008	0.276x10 ⁻³
X62	0.00285±0.00001	0.00213±0.00005	0.0114±0.0001	0.152x10 ⁻³
X63	0.00285±0.00001	0.00296±0.00028	0.0122±0.0004	0.246x10 ⁻³
Edge X50	0.00358±0.00028	0.00476±0.00028	0.0094±0.0014	0.433x10 ⁻³

* Values taken from curve

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TABLE 3.3

COMPACT VS ROD CELL BASED ON EQUIVALENT MASS

<u>Position</u>	<u>Compact-Rod Cell No Mass Correction %Δk</u>	<u>Rod Cell Correction Due to Mass Differences %ΔK</u>	<u>Compact-Rod Cell After Mass Correction %ΔK</u>
0	+0.0235 $\pm$ 0.0008	+0.0362 $\pm$ 0.0010	-0.0146 $\pm$ 0.0012
X30	+0.0222 $\pm$ 0.0013	+0.0222 $\pm$ 0.0013	-0.0111 $\pm$ 0.0023
X50	+0.0173 $\pm$ 0.0019	+0.0239 $\pm$ 0.0024	-0.0066 $\pm$ 0.0031
X51	+0.0242 $\pm$ 0.0008	+0.0266 $\pm$ 0.0016	-0.0024 $\pm$ 0.0018
X62	+0.0161 *	+0.0162 $\pm$ 0.0003	-0.0001 $\pm$ 0.0003
X63	+0.0207 *	+0.0218 $\pm$ 0.0018	-0.0011 $\pm$ 0.0018

* Where there are no standard deviation error values given, there was only a single measurement.

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across the reactor were summed to give a net effect of placing only compact fuel elements in the reactor. The result was a decrease in reactivity of approximately $0.85\% \Delta k$. This value, however, has quite a large uncertainty (approximately 50%) as is indicated by Figure 3.7.

No corrections were made for any significant change in tungsten and oxygen worth at the extreme radial edge of the reactor. This over-all correction would be small (about 1.0%) because of the very thin reflector and essentially insignificant low energy flux being reflected into the core.

There was some question after these measurements and comparisons were completed concerning the results showing the compact cell to be worth less than the rod type cell. To check the effect of lumping the materials in the form of rods as was done in the rod cell, all of the fuel rods were placed in the center of the fuel element in position X63. The same rods were used in the cell as prior to their re-arrangement. There was no measurable change in reactivity. The same measurement was then made in the center of the reactor, and the lumping of the fuel caused an increase in reactivity of $0.0493 \pm 0.0017\% \Delta k$. There is a positive effect, therefore, due to lumping the materials in the form of rods towards the center of the reactor. This is analogous to what is shown in Figure 3.7. The rod type cell is worth increasingly more than the compact cell as the comparison is made from the outside towards the center of the reactor. At the edge of the reactor, the two types of fuel elements show essentially the same reactivity effects.

The final loading of the Mockup 1C reactor contained some fuel cells which were slightly different than the initial Mockup 1C loading. This was necessary, in part, to adjust k-excess to the desired level. The base excess reactivity was $0.0986\% \Delta k$ with the following deviations from a reference Mockup 1C loading.

1. 31 Cells around the core center were one fuel rod deficient and one W rod excess
2. 4 compact fuel elements were in the reactor
3. There were two extra 1/2-hexes of Be in the reflector over the required one-hex layer of Be reflector.

The corrections required to adjust for the above items are as follows:

Base k-excess	+0.0986% Δk
Corrections for four compacts	-0.0783% Δk
Addition of 31 fuel rods	+1.5458% Δk

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Removal of 31 W rods	-0.0415%Δk
Removal of 2 Be 1/2-hexes	<u>-0.1894%Δk</u>
Net	+1.3352%Δk

This value is the extrapolated excess reactivity of a fully loaded Mockup 1C rod type reactor. The equivalent compact fuel element loaded reactor would be expected to have an excess reactivity of 0.5%Δk.

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4.0 NEUTRON LIFETIME MEASUREMENTS

The neutron lifetime (or generation time) was determined by two different methods. The "dynamic-statistical" method known as Rossi-alpha was used to measure the rate of decay of the prompt neutrons in the reactor. Several characteristic decay rates were observed, depending on the coupling between the core and reflector and the relative contributions of each of these coupled modes to the reactor multiplication. The static method of determining the neutron lifetime is to use a $1/v$ -absorber and essentially average the neutron reciprocal velocity, weighted by both the direct and adjoint fluxes. The general formulas and methods used for these measurements are discussed in Section 4.1 of Reference 1.

4.1 Rossi-Alpha Measurements

The Rossi-alpha measurements were made by the usual method of recording the time interval between an initiating "fission-chain" pulse in a "trigger" chamber and the subsequent pulse in the "counting" chamber. Counts are accumulated at low power until sufficient statistics are obtained to determine a decay rate or rates plus the over-all uncorrelated background level. A 256-channel analyzer with channel-width selection between 0.25 and 64 microseconds was used. The data was fit to a double exponential decay plus background by a least squares program. Where double exponential decays could not be defined, a single decay was employed. The combined results of numerous measurements at various channel widths are given in Table 4.1

As noted, there were generally three components of decay found for the 710 Mockups 1A and 1D (and for the 710 Basic Critical Experiment) but only two for the 710 Mockup 1C. In the latter case, the slow component was poorly defined, and was due to the relatively few lower energy (thermal and resonance neutrons) being returned to the core by the thin reflector. In general, it is believed that the history of the neutrons contributing to the fast decay consist of neutron velocities characteristic of the main core spectrum. This group can include direct, single-collision back-scatterings from the reflector, during which the neutron energy is decreased only 20%. The intermediate component, the least precisely defined component of the three, is thought to be associated with neutrons slowing down in the reflector to the resonance region and then returning to the core to be absorbed. The slowest decay component is believed to be due to neutrons undergoing a nearly complete moderation in the reflector before being returned to the core as essentially thermal neutrons. It may be argued that the intermediate component is most likely a continuum of lifetimes and the difficulty of defining a precise value for it supports this contention. In fact, the entire continuum of lifetimes blend together to the extent that on the optimum time-channel width for the fast decay (0.25 microsecond), the lower two components

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TABLE 4.1

ROSSI-ALPHA DECAY COMPONENTS AT DELAYED CRITICAL

	<u>Mockup 1A</u>	<u>Mockup 1D</u>	<u>Mockup 1C</u>	<u>Basic Critical Experiment</u>
Reflector thickness (cm)	18.9	10.4	4.2	15.5
Fast α (microseconds) ⁻¹	0.33±0.01	0.21±0.02	0.167±0.012	0.30±0.01
Intermediate α (microseconds) ⁻¹	0.025±0.010	0.017±0.001	0.055±0.020 ⁽¹⁾	0.022±0.008
<u>Amplitude Intermediate</u> <u>Amplitude Fast</u>	0.11±0.03	0.15±0.02	0.04 ⁽¹⁾	0.15±0.02
Slow α (seconds) ⁻¹	900±50	6000±800	---	1200±200
<u>Amplitude Slow</u> <u>Amplitude Fast</u>	0.06±50%	0.2±0.1	---	0.10±0.05
"Core" Multiplication Factor	0.88	0.94	0.98 ⁽¹⁾	0.90
Effective 1/v Lifetime (microseconds)	7.0±0.5	1.32±0.09	0.24±0.05	5.6±1.0

(1) The reflector component was very poorly defined and the relative amplitude quite uncertain.

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blend together while on the optimum channel width for defining the slowest component (32 to 64 microseconds), the faster two components generally blended together.

Attempts at determining the core multiplication factor (by definition the multiplication due to the fast component) by making the system subcritical was done on the Mockup 1A. The following results were obtained:

Mockup 1A - Fast Decay ;

At delayed critical	(0.33 ± 0.01) microseconds
At 0.62%Δk subcritical	0.353 microseconds
At 1.20%Δk subcritical	0.386 microseconds

This data extrapolates to an intercept for $\alpha = 0$ at 7.1% supercritical.

From the relation:

$$1) \quad \Delta k_c = \frac{1 - k_c (1 - \beta)}{k_c (1 - \beta)},$$

this implies that the core multiplication factor is 0.937. However, the subcriticality of the reactor was altered by withdrawing control bars near the core interface. This affects the contribution to the reactor multiplication from all three decay components. Thus, the core multiplication factor is probably lower than 0.937, perhaps in the neighborhood of 0.90. The contribution to the reactor system multiplication from only subcadmium neutrons (below 0.5 ev) was measured on the Mockup 1D to be 2.36%Δk, and a similar result should apply to the other Mockup 1 reactors. (On the Basic Critical Experiment, the effect of a cadmium circumferential core-shield was 2.7% Δk.)

The equations used for the purpose of synthesizing neutron lifetime components and "effective average" lifetimes from the decay data are presented in Reference 4. These are summarized as follows:

$$2) \quad \text{Core-Lifetime} = \ell_c = \frac{1 - k_c (1 - \beta)}{\alpha_c}$$

$$3) \quad \text{Reflector Lifetime Component } i = \ell_{ri} = \frac{k_c \beta}{\alpha_{ri} [\Delta k_{ri} + \beta]}$$

- (4) Kunze, J. F. and Sims, F. L., "Neutron Lifetime Measurements On a Two-Lifetime Component Critical Experiment by the Rossi-Alpha Technique," GEMP-281, April, 1964.

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Contribution to multiplication of reflector component i =

$$4) \quad \Delta k_{ri} \sim k_c \beta \frac{A_{ri}}{A_c} \frac{\alpha_c}{\alpha_{ri}}$$

$$5) \quad \text{where } k_c + \sum \Delta k_{ri} = 1.0$$

$$6) \quad \text{Effective } 1/v\text{-lifetime} = \ell_{\text{eff}} = \sum_i \Delta k_i \ell_i + k_c \ell_c$$

Equation (4) is an approximate method of obtaining the contribution to the multiplication factor of the reflector components from the relative amplitudes, A, of the decay components. In the above, subscripts "c" refers to the core and "r" to the reflector.

Using the above equations, the mutual constraints between Equations (4) and (5), and the supplementary constraint from the subcritical data (Equation 1), the values listed in Table 4.2 were deduced. The over-all average lifetime (herein called the 1/v-effective lifetime) is relatively insensitive to the values chosen for the contribution to the multiplication factor of the various components. This effective lifetime reduces approximately to:

$$7) \quad \ell_{\text{eff}} \sim \frac{k_c \beta}{\alpha_{r \text{ slow}}}$$

if α_r for the slow component is an order of magnitude different from any of the other components and contributes several percent or more to the systems' multiplication factor. In fact, changing the core multiplication factor from 0.94 to 0.88 on the Mockup 1A only reduced the effective lifetime by 5%.

4.2 1/v Poisoning to Determine the Prompt Neutron Lifetime

Measurements of the prompt neutron lifetime were made by poisoning the Mockup 1 with boron-10, a 1/v absorber from thermal energies to approximately 2 Mev. The uniform atomic density was approximated in the 710 Critical Experiment Reactor by incrementally poisoning the assembly with small and dilute amounts of B-10. The locations at which these measurements in the Mockup 1C were made, for instance, are shown in Figure 4.1. The reactivity change related to B-10 was determined by inserting the poison in the form of B-Al or B-SS. The B-Al, with a B-10 concentration of 0.385%, was used in the core and the B-SS with a natural boron concentration of 1.05% was used in the void and in the radial reflector. In each case, the worth of B-10 was determined by measuring the worth of the base material, SS or Al, and correcting the worth of the borated samples. Table 4.3 and Figures 4.2 to 4.4 present the resultant B-10 radial worth function in % Δk per gram at the various measurement locations. The reactivity change associated with a known atomic density was

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TABLE 4.2

ROSSI-ALPHA NEUTRON LIFETIME SUMMARY

	<u>Mockup 1A</u>	<u>Mockup 1D</u>	<u>Mockup 1C</u>	<u>Basic Critical Experiment</u>
k_c (core)	0.88	0.942	$0.98^{(1)}$	0.905
Δk_r -fast (intermediate component)	0.02	0.012	$0.02^{(1)}$	0.015
Δk_r -slow (thermal)	0.10	0.046	---	0.08
l_c (core) microseconds	0.38	0.31	0.16	0.33
l_r -slow (thermal) microseconds	64.7	20.7	---	63.7
l_r -fast (intermediate) microseconds	13.0	6.3	4.7	13.7
$l_{eff}^{-1/v}$ microseconds	7.0 ± 0.5	1.32 ± 0.09	0.24 ± 0.05	5.6 ± 1.0

(1) These values were poorly defined by the data and were largely assumed from comparison with the 1A and 1D configurations.

-58-
CONFIDENTIAL

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TABLE 4.3

BORON-10 $1/v$ ABSORBER REACTIVITY COEFFICIENTS: $-\% \Delta k/\text{gram B-10}$

	Mockup 1A	Mockup 1C	Mockup 1D	Basic Critical Experiment
Core Center	$(0.76 \pm 0.04) \times 10^{-2}$	1.35×10^{-2}		$(1.3 \pm 0.1) \times 10^{-2}$
7.5 cm inside core edge		0.89×10^{-2}		
5.0 cm inside core edge	0.95×10^{-2}			
3.8 cm inside core edge		0.12×10^{-2}		
1.5 cm inside core edge				2.9×10^{-2}
Core Edge				$(3.3 \pm 0.2) \times 10^{-2}$
Core Average	1.7×10^{-2}	0.57×10^{-2}	$(2.3 \pm 1.0) \times 10^{-2}$ (3)	2.1×10^{-2}
Core shell, inner surface		1.77×10^{-2}	$(8 \pm 3) \times 10^{-2}$	
Core shell, outer surface (1)	$(11.2 \pm 1.1) \times 10^{-2}$			
1/2 hex Be from core (1)	17.2×10^{-2} (2)	$(0.04 \pm 0.04) \times 10^{-2}$	6.3×10^{-2}	46.8×10^{-2}
1-1/2 hex Be from core (1)	22.9×10^{-2} (2)		0.21×10^{-2}	35.3×10^{-2}
2-1/2 hex Be from core (1)	12.8×10^{-2} (2)			3.9×10^{-2}

- (1) These values do not include a self-shielding correction of nominally 10%.
- (2) The Mockup 1A radial reflector measurements were taken in typical cells and not at specific radii. The results reported are therefore interpolations.
- (3) The measured value for the core average in the 1D probably is high, since the material was arranged to favor the regions near the core edge.

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-60-

Fixed Table

Figure 4.1

Mockup 1C B-10 Worth
Measurement Locations

[REDACTED]

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Figure 4.3
Mockup 1C
NORMALIZED B-10 WORTH*
VS
RADIAL DISTANCE

*Worth of 10^{21} B-10 atoms/cm³
0.635 cm thick ring volume

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1C

41.

CONFIDENTIAL

-62-

Normalized B-10 Worth (%Δk)

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-65-

B-10 Worth ($\% \Delta k / \text{gram} \times 10^2$)

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normalized to give the effect that 10^{20} B-10 atoms/cm³ would produce, and the total worth determined by taking the integrated total throughout specific regions of the assembly, i.e.,

$$\Delta k \left(10^{20} \frac{\text{B-10 atoms}}{\text{cm}^3} \right) = c \int_{\text{region}} \frac{\Delta k}{V} dr$$

where Δk = The reactivity change of a known atomic density in a right cylindrical ring volume V with a ring thickness of Δr

c = conversion constant of the appropriate dimensions to convert the measured reactivity in $\% \Delta k / \text{gm}$ used to a reactivity per unit volume per 10^{20} atoms per cc.

Figure 4.3 shows the space dependence of worth per unit 1/4-inch thick radial ring, in this case for the Mockup 1C. From the areas under this curve either the average or total worth in a particular region of the reactor can be easily determined.

An attempt was made to uniformly poison the end reflector by inserting B-SS strips into the holes of the plugs; however, the results indicated that this was comparable to adding the poison to the outside of the radial reflector i.e., the worths were very small and invariably positive due to the scattering cross-section and are therefore not a measure of the amount of absorption. For this reason, the front reflector results were assumed from the results obtained with the Basic Critical Experiment, in which merely an upper limit to the effect was determined. Note, that the front reflector was treated separately, from the radial data, the latter referring to core length (14.76 inches) measurements throughout the core gap regions and radial reflector. The measurements in the 1A radial reflector actually were made over an 18-inch length, and included a region of the front reflector, but the contribution to the total worth was less than the uncertainty quoted for the front reflector result. (These dimensions do not apply to the Basic Critical Experiment, which has been included in Table 4.4 only for comparative purposes.)

The results of the poisoning of the reactor with 10^{20} B-10 atoms/cc are listed in Table 4.4. In converting the direct measurements to these results, it was assumed that the worth in the entire gap was approximately the same as that measured either just inside the core shell or inside the beryllium reflector, i.e., that the worth was constant across this gap, to within 10%. Furthermore, a 7% self-shielding factor was applied to the "gap" data and a 10% self-shielding factor to the "radial reflector" data. The latter factor is approximately the flux perturbation factor of the boron strips

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TABLE 4.4

1/v-LIFETIME MEASUREMENTS IN MOCKUP 1Worth of 10^{20} B-10 Atoms per Cubic Centimeter

<u>Reactor Component</u>	<u>Mockup 1A</u>	<u>Mockup 1D</u>	<u>Mockup 1C</u>	<u>Basic Critical Experiment</u>
Front Reflector (%Δk)	0.3±0.2	0.3±0.2	0.3±0.2	0.4±0.3
Radial Reflector ⁽¹⁾	43.0±4.5	4.1±0.5	0.20±0.1	37.8±3.0
Core	1.44±0.10	1.95±0.6	0.48±0.06	0.8±0.2
Gap Region ⁽¹⁾	<u>5.3±1.0</u>	<u>4.7±0.8</u>	<u>0.75±0.20</u>	<u>---</u>
Total (%Δk)	49.3±4.7	11.1±1.1	1.7±0.3	39.0±3.1
Neutron Lifetime				
$= \frac{\Delta k}{3840 \text{ barns} \times 2200 \text{ m/sec} \times 10^{20}} \quad (\text{microsecond})$				
	(5.8±0.6)	1.31±0.13	0.20±0.04	4.6±0.4
Reduced 1/v lifetime from Rossi-Alpha (microsecond)				
	7.0±0.5	1.32±0.09	0.25±0.05	5.6±1.0

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- (1) All values in the gap region were obtained from the measured data plus 7% for self-shielding correction in the boron. The radial reflector data includes a 10% self-shielding correction. The "gap" refers to the void, core shell, and aluminum transition region out to the beryllium.

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to a thermal flux, which contributed nearly 90% of the total worth in typical reflector fluxes of the Mockup 1A. The total contribution of 10^{20} atoms/cc over the entire reactor and the resultant $1/v$ -effective neutron lifetime are also listed in Table 4.4.

4.3 Boron Measurements of Low-Energy End of Core Spectrum

Two rod-shaped samples of boron powder were measured in the radial center of the core of the Mockup 1A, extending the full core length, in an effort to determine at what physical thickness of boron self-shielding begins to occur. The thickest sample would have created a 10% flux perturbation at 4.5 Kev within a carbon medium (Reference: Dalton and Osborne, NSE, February, 1962, Page 191). There was only a $(5 \pm 3)\%$ reduction in worth of this larger sample compared to a smaller sample that was only 45% as thick, nuclearly. Though the reduction in worth was observed on separate measurements made both over the full core length and only in the reflected end of the core, the results are still considered too uncertain to conclude anything more significant than that there apparently is very little flux below 4.5 Kev in the radial core center. Any such low energy flux probably contributes less than 50% of the total worth of a $1/v$ -absorber. The latter implies that the flux per unit energy is probably dropping faster than $\sqrt{E}$ in the region of 4.5 Kev.

The results of the boron-10 worth at the radial center of the core were

$$(0.0076 \pm 0.0004)\% \Delta k / (\text{gram B-10})$$

measured over the full core length,

$$\text{and } (0.0085 \pm 0.0003)\% \Delta k / (\text{gram B-10})$$

measured over 6-inches at the reflected end of the core.

4.4 Comparison of Static - $1/v$ -Poison and Rossi-Alpha Lifetime Results

The "effective neutron lifetimes" (average) as determined from the reduced Rossi-alpha data are compared with the results of the $1/v$ -absorber lifetime in Table 4.4. The process of reducing the Rossi-alpha results to an "average" effective lifetime utilized equation (6) in Section 4.1 of this report, by which the total effective lifetime is the sum of the products $\Delta k \cdot \lambda$. The exact equivalence of those results to the statically measured (absorber) result may not be rigorous. However, the two results generally agree within the assigned errors (nominally standard deviations). The Mockup 1C result is the most uncertain, principally because of the difficulty of defining the slow decay component in the Rossi-alpha work and the relatively poorly defined curve in the core for the absorber result. It was only in the Mockup 1C case that the core contributed a major portion to the average (effective) lifetime of the system. In the other three configurations, the reflector was the major contributor.

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The relative contributions of the various regions and decay components to the reactor lifetime are listed in Table 4.5. Note that the $1/v$ results for the core and front reflector are generally somewhat less than that calculated from the fastest alpha decay contribution. This discrepancy is to be expected, for the Rossi-alpha result includes reflector effects of direct reflections, whereas the equivalent $1/v$ result should include some reflector poisoning. The slowest alpha decay requires that both the gap and reflector contributions of the $1/v$ result be summed to give favorable correlation. The intermediate decay component does not seem to be identified with any particular $1/v$ -measurement region. This intermediate component generally makes an insignificant contribution to the total effective lifetime, and therefore is probably characteristic of the nearly continuum of lifetimes between those characteristic of the core alone and those contributed by the strongly absorbing, well moderated components associated with the slowest decay (due to the reflector). Except for the 1C configuration, it was this latter component that almost exclusively established the value of the net effective (average) lifetime from the Rossi-alpha results. The error on the effective lifetime so determined is essentially the error on the value of this slowest alpha decay.

With reference to the threshold poisoning measurements reported in Section 4.3, the lowest energy flux in the core center is in the neighborhood of 4 Kev. However, near the reflector, the flux obviously reaches much lower energies. Therefore, had the lifetime been measured in a bare core, the results would have been substantially less than those reported in the first two lines of Table 4.5.

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TABLE 4.5

CONTRIBUTION OF COMPONENT LIFETIMES (in microseconds) TO $1/v$ EFFECTIVE LIFETIME

		<u>Mockup 1A</u>	<u>Mockup 1D</u>	<u>Mockup 1C</u>	<u>Basic Critical Experiment</u>
I.	Fast, from Rossi- α	0.33	0.29	0.16	0.30
	Boron Poison, Core and Front Reflector	0.21 $\pm$ 0.03	0.27 $\pm$ 0.08	0.09 $\pm$ 0.03	0.14 $\pm$ 0.04
II.	Intermediate, Rossi- α	0.26	0.06	0.09 $\pm$ 0.03	0.28
	Boron Poison, Gap Region	0.50 $\pm$ 0.12	0.56 $\pm$ 0.10	0.08 $\pm$ 0.02	---
III.	Slow, Rossi- α	6.5 $\pm$ 0.4	1.04 $\pm$ 0.08	---	5.1 $\pm$ 0.9
	Boron Poison, Radial Reflector	5.1 $\pm$ 0.5	0.49 $\pm$ 0.06	0.02 $\pm$ 0.01	4.5 $\pm$ 0.4

~~CONFIDENTIAL~~

-68-

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

5.0 FISSION RATIO MEASUREMENTS IN THE CORE FLUX

The fission rates of several different isotopes were measured at the core center of each of the Mockup 1 assemblies using miniature absolute chambers. The chambers were located approximately 0.25-inch off the separation plane in cell 0 of the fixed table. The chambers were positioned in an aluminum tube and the core materials were distributed around the tube, and behind the chamber. The fuel composition of the cell was maintained, however, no compensations were made for the deficiencies related to the other materials of the cell.

In addition to the absolute fission chambers, catcher foils were exposed on the end of the chambers and the U-235 fission rate determined by this means. *

Table 5.1 gives the ratio of fission rates of Th-232, U-238, Pu-240, Np-237, Pu-239 and U-233 to that of U-235, on an atom per atom basis. These data were obtained after appropriately normalizing all runs to the same power level through the use of gold foil activation rates corrected to the reactor shutdown time for each exposure. Where standard deviations are not shown in Table 5.1, the measurements were made only once and uncertainties can be expected to be the same magnitude as those appearing elsewhere in the table, nominally 2%.

The fission ratio data related to the Mockup 1C are all slightly lower than those obtained in the Mockups 1A and 1D, the other uniformly loaded reactors which had a thicker reflector. The implication of these results is that the Mockup 1C had a slightly softer spectrum at the core center than did these other configurations.

It is not obvious why a softer spectrum would be present in the more heavily loaded core. However, the first four fission ratios in Table 5.1 are primarily high-energy spectral indices, since the fission thresholds of these fissionable isotopes are above 0.4 Mev. Thus, the lower fission ratios in the 1C, although not outside the experimental uncertainty but still uniformly consistent, may be the result of the greater inelastic scattering in that core. It should be noted that this difference is not nearly as significant as the hardening of the spectrum in moving from the center toward the open end (7 cm position) of the Mockup 1A core.

*

Catcher foil fission rates had been determined from a calibration of foil activity following exposure in a known flux. The conversion constant of 57.3 fission/sec/gm per count per minute at 50 minutes after shutdown from 2 π beta counters averaged 3% high when compared to the directly measured fission rates with the absolute U-235 chamber.

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Comparison of the Mockup 1 fission ratios with those of the Basic Critical Experiment shows that all of the fissionable isotope fission rates are higher in the latter, while the fissile materials appear to fission at proportional rates in both configurations. The principal difference is due to the oxygen "moderator" in the Mockup 1 configurations. The three fissile isotopes measured are nominally $1/v$ in cross-section below about 0.07 Mev, and differences in these fission ratios between the two assemblies would not be expected.

~~CONFIDENTIAL~~

-70-

TABLE 5.1

FISSION RATE RATIOS PER ATOM

		<u>Mockup 1A</u>				Core Center of Basic Critical Experimental ($\pm 2\%$)
	<u>Core Center</u>	<u>Interface at Front Reflector</u>	<u>7 cm From End</u>	<u>Mockup 1C Core Center</u>	<u>Mockup 1D Core Center</u>	
Th-232/U-235	0.019 $\pm$ 0.001	0.014	0.021	0.0185	0.0195	0.022
U-238/U-235	0.072 $\pm$ 0.002	0.048	0.078	0.071	0.072	0.083 $\pm$ 0.003
Pu-240/U-235	0.48 $\pm$ 0.01	---	---	0.46	0.49	0.525
Np-237/U-235	0.49 $\pm$ 0.02	---	---	---	---	0.56
Pu-239/U-235	1.19 $\pm$ 0.02	1.21	---	---	---	1.19
U-233/U-235	1.53 $\pm$ 0.05	---	---	---	---	1.56

All results are expected to have standard deviations of nominally $\pm 2\%$ unless otherwise indicated.

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6.0 SPECTRAL SYNTHESIS FROM CADMIUM RATIO MEASUREMENTS IN THE REFLECTOR

Resonance foil-detectors of indium (1.44 ev), gold (4.96 ev), manganese (337 ev) and Oralloy (principally 1.1, 3.6 and 8.8 ev resolved resonances, plus high energy unresolved resonances) were exposed in the reflector regions of the Mockup 1 reactors. From these measurements, spectral indices and general neutron energy dependence over the region of the resonances could be deduced. The foils were exposed both in cadmium covers and as bare foils so as to separate the sub-cadmium (thermal) response from the resonance region response. Since all of the above detectors are essentially $1/v$ detectors below the effective cut-off for 0.020 inch thick cadmium (nominally 0.5 ev), the sub-cadmium response of each served as a direct experimental normalization for the absolute activation rates, without a need to depend upon the direct absolute measurement of disintegration rates.

In general, all bare and cadmium covered exposures were repeated at least once to assure that normally expected experimental anomalies were identified and discarded. Corrections to the epi-cadmium results were made to account for the finite foil thickness so as to convert the measured cadmium ratios to those of an infinitely dilute detector. Figure 4.3.2 of Reference 1 is an illustration of the aforementioned results obtained with the 710 Basic Critical Experiment. For instance:

$$\text{Cd Ratio} = \frac{\text{Epi-Cd. plus Sub. Cd. Activities}}{\text{Epi-Cd. Activity}}$$

$$\text{Cd Ratio} \Big|_{\infty} = \frac{I_{\text{eff}}^{\text{Cd}}}{I_{\text{eff}}^{\text{Bare}}} + [(\text{Cd Ratio} - 1)]_{\text{measured}} \frac{I_{\text{eff}}^{\text{Cd}}}{I_{\infty}^{\text{Cd}}},$$

where I_{eff} is the effective resonance integral for the foils, bare or cadmium covered as indicated.

The measured and corrected (infinitely dilute) cadmium ratios for the Mockups 1A, 1C and 1D are listed in Table 6.1. Values shown without standard deviations are results obtained from a single measurement (note that the errors are not shown on the dilute value if they already appear for the measured result). The gold foil results on the Mockup 1A were obtained with 0.5 mil thick foils whose average thickness varied sufficiently to give the directly measured values a large variation. When corrected to infinite dilution, the results had the spread (standard deviation) shown. The Oralloy (93.2% enriched uranium) cadmium ratios were determined from catcher foil activations, i.e., aluminum disks placed against 0.001-inch thick foils of Oralloy. Foils of this thickness create an average flux perturbation of approximately 13% in a thermal flux, with reference to the average fission rate in the foil. However, the

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sensitive region for the catcher foils was approximately the outer 0.0001 inch, hence essentially the surface activation was measured. In the resonance region, the surface activation of the $1/v$ portion of the resonance integral is essentially the same as the volume activation, while the activation from within the resonances is affected in a similar manner as the thermal flux, since the principal resonances have peak magnitudes comparable to the thermal cross section of 683 barns. The $1/v$ contribution to the resonance integral is 305 barns out of a total of 440 barns. Hence, the net anticipated correction to the resonance activity is less than 4%. For example, calculations* of a cadmium ratio based on a volume activation of 0.001-inch thick uranium gave 4.91, while the surface activation ratio was 4.82. No correction was made for thermal flux depression in the surrounding beryllium medium, an effect which is less than 5% and hence much smaller than the net experimental uncertainties shown for the thermal to epithermal ratio of activity.

Synthesis of a spectrum within the resonance region was done by using effective group cross sections derived from measured resonance integral data. The 16-group format of the NMPO cross sections, similar to the Hansen-Roach set, (Reference 5) was used. The resonance integral data was generally obtained from Reference 6. Calculation of group fluxes was done using the cross sections listed in Table 6.2. Solution of the equation set

$$M_{xy} \phi_y = \left(\left[\frac{\tau_{\text{thermal}}}{(\text{Cd. Ratio}) - 1} \right] \right)_x$$

was obtained for the vector matrix ϕ_y , with y being the index of the energy group, x the index of the detector material.

The resulting group fluxes were fit to a straight line on the semi-logarithmic flux per unit lethargy scale, giving

$$\ln \phi(u) = -(1-x) u$$

$$\text{or } \phi(E) = \frac{\phi_0}{E^x}$$

(For the flux spectrum in an infinite, non-absorbing, diffusing medium, the exponent x is 1.0.)

* W. B. Henderson, private communication, the results of a detailed calculation of the effect over the entire foil thickness by transport theory were included.

- (5) Robertson, C.S. and Benson E., "Nine and Sixteen Group Cross-Sections for Reactor Analysis," GEMP-173, 1-18-63, and Supplement # 1, 9-1965.
- (6) Persiani, McCarthy, et al, "ANL Reactor Physics Constants Center News-letters," # 1, 10 and 11 Argonne National Laboratory.

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The results of the spectral fits at various regions of the Mockup 1 reflectors are listed in Table 6.3 and typical spectral fits are shown in Figure 6.1. The exponents were all well defined, to within ± 0.02 , except that for the Mockup 1D, where experimental anomalies and lack of repeated data made the results questionable. The hardest spectrum was inside the thin (4 cm thick) reflector of the 1C, while the spectrum at the outside of the 20 cm reflector of the 1A was nearly $1/E$ in shape. A relative indication of the hardness of the spectra is also given by the ratio " f " in Table 6.3, this ratio being the conventional thermal (sub-cadmium) flux to the flux per unit lethargy at 1 ev. The two values shown on the spectral-fit-plot for the group 3 cross section of manganese refer to an 11 and 15 barn total resonance integral, respectively. The $1/v$ contribution to the manganese resonance integral is rather accurately known to be 5.9 barns *, but the early data gives the resonance contribution as 5 barns, while more recent data shows it to be 9 barns. The 5 barn value gave the smoothest fit to the experimental data. Accounting for the hardness of the spectrum in calculating effective average cross sections for manganese in the $1/v$ region improved the spectral fit slightly, but still left the 5 barn resonance contribution as giving the smoothest fit, as illustrated in the Figure 6.1. **

A more exact matching of the cross sections in the low energy group with the correct cadmium cutoff value would improve the accuracy of the spectral fit, but only slightly. A cut off of 0.5 ev (the standard assumption) is somewhat below the appropriate value for indium under a 0.020-inch thick cadmium cover (Reference 7), but is approximately correct for gold and other more-nearly- $1/v$ absorbers in the region of the cut off. The effects on the effective resonance integral are also relatively insignificant, due to the presence of the 0.020-inch cadmium cover, being most severe for indium for which the correction is approximately 5%. These various corrections are insignificant compared to the nominal 5% to 20% uncertainties in the data for the ratio of sub-cadmium to epi-cadmium activity.

* From an effective cadmium cut off of 0.6 ev.

(7) A cut off of about 0.8 ev seems more reasonable, for instance Page 12 of the work of Brown, H. L., and Conolly, J. J., "Nuclear Science and Engineering," Volume 24, (January, 1966) Page 6.

** Note added in proof. Calculations of the self-shielding effect of the scattering width in the major manganese resonance indicates an effective reduction of the non- $1/v$ portion of the resonance integral by approximately 2 barns. (Private communication from W. B. Henderson) Furthermore, recent cross section compilations (see for instance W. P. Keeney, Trans. ANS, Vol 9, No. 1, June, 1966, page 187). Thus the implied 11 barn resonance integral from the spectral fitting is consistent with these latter results.

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TABLE 6.1

CADMIUM RATIOS ⁽¹⁾ IN THE REFLECTOR OF MOCKUP 1
CONFIGURATIONS

Material Reactor Position	Indium		Gold		Manganese		Oralloy
	Measured	Dilute	Measured	Dilute	Measured	Dilute	Dilute
1A-inside shell	---	---	(2)	1.16±0.03	3.65	3.48	4.2±0.1
1A-outside shell	---	---	(2)	1.21±0.03	3.71	3.63	5.25
1A-1 hex	---	---	(2)	1.26±0.03	4.68	4.46	7.8
1A-2-1/2 hexes	---	---	(2)	1.35±0.02	7.88±0.08	7.51	12.1±0.1
1A-outside	---	---	(2)	1.38±0.01	9.9±0.6	9.46	14.6±0.2
1C-1/2 hex	1.055±0.035	1.04	1.072±0.021	1.01	1.106±0.020	1.10	1.060±0.014
1D-1/2 hex	---	---	1.08	1.06	1.50	1.48	---
1D-1-1/2 hexes	1.88	1.94	1.16	1.12	2.42	2.35	3.82

(1) The cadmium ratio is defined as bare foil activity divided by cadmium-covered foil activity.

(2) The foil thickness varied among the various measurements, which were corrected to give the infinitely dilute values shown.

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TABLE 6.2

GROUP STRUCTURE AND CROSS SECTIONS (barns) FOR SPECTRAL SYNTHESIS

<u>Group</u>	<u>Upper Energy</u>	<u>Lethargy Width</u>	<u>σ In</u>	<u>σ Au</u>	<u>σ Mn</u>	<u>σ U-235</u>
0	thermal	---	143	87	11.7	509
1	1.855 ev	1.0	2500	20	2	50
2	61.44	3.5	0	444	0.8	50
3	0.454 kev	2.0	0	30	(2.5) 4.5	17.7
4	17.0 kev	3.62	0	0	0	6.1

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TABLE 6.3

SPECTRUM IN REGION OF 0.6 ev to 17 Kev, FIT to $\phi(E) = \phi_0/E^x$

<u>Reactor and Position</u>	<u>Number of Energy Groups</u>	<u>Spectrum Exponent x</u>	<u>f *</u>
1A - inside shell	3 + thermal	0.55	6
1A - outside shell	3 + thermal	0.64	5.5
1A - 1 hex	3 + thermal	0.71	7
1A - 2-1/2 hexes	3 + thermal	0.82	9
1A - Outside	3 + thermal	0.86	10
1C - 1/2 hex	4 + thermal	0.43	0.7
1D - 1-1/2 hexes	3 + thermal	0.6 ± 0.1	5

* f is the ratio of "thermal" flux to slowing down flux per unit lethargy at 1 ev.

16

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7.0 POWER DISTRIBUTION MEASUREMENTS

Unclassified
The fission power distributions on the three reactors (Mockup 1A, 1C and 1D) had generally similar longitudinal distributions with the power shifted toward the front reflector, the peak power occurring approximately 15 cm from the front reflector (total core length 37.5 cm). The radial profiles, however, differed substantially, due to the different reflector thicknesses on the three reactors. The Mockup 1A had a sharply peaked power distribution at the radial core boundary; the thinner reflector of the Mockup 1D had a modifying influence upon the power peak; and the very thin reflector of the Mockup 1C essentially had no peaking at the core boundary. Elimination of the power peak also eliminates the advantageous gross radial power flattening provided by the reflector. Thus, the Mockup 1C had the greatest center peaking of the power of the three reactors.

The effect of the ragged outer core boundary, due to the hex structure of the cells, was investigated in detail on the Mockups 1C and 1D. On the former core, with its nearly flat power distribution in the outer cells, the boundary effect was extremely minor, with total variations being less than 15%. However, on the Mockup 1D, with its peaked power in the outer cells, the relative total variation of 20% along the outer boundary was quite significant because of the high over-all average magnitude of this peak, which was nominally 1.5 times the core-center power. Furthermore, on the latter configuration, the minimum power magnitude within the protruding outer cells (such as 150), was slightly less (nominally 7%) when measured in the homogeneous cell as compared to the rod cell. The rod cell permitted more of the reflector flux to reach the location of the minimum, thus enhancing its value.

The specific results of the power distribution measurements on each reactor are given in the following sections. Table 7.1 summarizes the major difference in power distribution between the three reactors and Figure 7.1 illustrates the relative radial power profiles of the Mockup 1 series of reactors with the comparison made at a single longitudinal location.

7.1 Mockup 1A Power Distribution

The 710 Critical Experiment Mockup 1A had a uniformly loaded core surrounded by a beryllium radial reflector which was 18.9 centimeters thick as shown in Figure 7.2. Power distribution measurements related to this assembly were made using aluminum fission product catcher foils to define the longitudinal and radial power. In order to obtain better definition of the power peak at the edge of the core, two special cells composed of sheet stock were assembled in such a manner to provide a homogeneous region. Catcher foils were distributed across these cells with the foil planes normal to their related radii.

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TABLE 7.1

POWER DISTRIBUTION SUMMARY (TYPICAL VALUES*)

	<u>Mockup 1A</u>	<u>Mockup 1C</u>	<u>Mockup 1D</u>
Reflector Thickness (cm)	18.9	4.2	10.4
(Max. Core-Edge/Core-Center) Ratio (Radial)	3.9±0.2	0.42±0.02	1.6±0.1
(Core-Center/Minimum) Ratio (Radial)	1.43±0.04	2.3±0.1	1.6±0.1
Position of Minimum from Core Edge (cm)	3 ± 1	0	2.5 ± 1
Longitudinal Power Peak	15 cm from reflected end		
(Peak/Reflected End) Ratio (Longitudinal)	1.6	1.7	1.6
(Peak/Unreflected End) Ratio (Longitudinal)	3.6	3.8	3.6

- * Typical values refer to the axial centerline in the case of longitudinal data and the separation plane of the tables (15 cm from the reflected end) for the radial data. Where circumferential differences are involved, the optimum or extremum conditions are quoted.

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Figure 7.2

710 REACTOR - MOCKUP 1A

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-82-

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7.1.1 Horizontal Radial Profile and Homogeneous Cell

The first complete radial profile measured was along the horizontal radius from the core center out to cell 150. The special cell made of sheet material, hereinafter called the "homogeneous" cell, was positioned in cell 150 and catcher foils distributed across the cell to obtain data related to the power peak at the core edge. Catcher foil bands were positioned at the edge and center of the core cells along this radius. The removal of pieces of aluminum tubing within a cell allowed catcher foil bands to be located at the inner portion of the cells without changing the volume fractions of the other core materials. The foil bands which were located in the center of the cells were backed with an extra piece of aluminum to shield the outer surface of the catcher foil from fission products coming from fuel rods in the cell. Figure 7.3 illustrates the geometry and orientation of the homogeneous cell and Table 7.2 presents a listing of the materials used in the homogeneous cell and the related comparisons to the rod type materials of the normal cell.

The data obtained from each exposure was normalized to the foil located at 13 cm from the reflected end of the core of the band positioned in Cell 0, hereinafter called the normalizer band. Figure 7.4 presents the average normalizer band longitudinal profile obtained from the fourteen separate exposures made during the power distribution measurements. The average standard deviation for the 12 points which define the normalizer band longitudinal profile is $\pm 1.03\%$.

A set of typical relative longitudinal power profiles from the bands positioned along the horizontal radius is presented in Figure 7.5 and three relative radial power profiles obtained by cross-plotting the longitudinal data are illustrated in Figures 7.6 through 7.8. Figures 7.9 and 7.10 are the profiles obtained from a repeat exposure of the homogeneous cell. The resultant power distribution parameters of center to minimum power ratio, peak to center power ratio, peak power, and location of minimum all as a function of longitudinal position are presented in Table 7.3.

7.1.2 Radial Profile at Table Separation Plane

The complete radial power profile was measured by exposing a catcher foil band which extended from the core center across the core radial gap and into the radial reflector. This band was attached to the core at the table separation plane (15.24 cm from the reflected end of the core) along the 30° radius. Since the plane of the foils was parallel to the table separation plane, small 0.25-inch diameter foils were punched from the band to obtain better resolution.

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Fixed Table
(Partial Core View)

Figure 7.3
HOMOGENEOUS CELL PLACEMENT

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TABLE 7.2

HOMOGENEOUS CELL COMPOSITION

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Material ⁽¹⁾	Table	Masses (grams)			
		Rod Cell ⁽²⁾	Homogeneous Cell ⁽³⁾		
Oralloy	M	714.02	672.0		
	F	1026.84	965.0		
Tungsten	M	878.56	827.0		
	F	1263.45	1188.0		
Tantalum	M	94.67	89.1		
	F	136.16	128.1		
Oxygen ⁽⁴⁾	M	90.2	84.8	88.5	80.0
	F	129.7	122.0	127.4	114.7

- (1) The thickness of the materials used were U = 0.004", W = 0.005" and 0.010", Ta = 0.001" and 0.002", teflon = 0.030".
- (2) The fixed table values are 0.985 of the core average cell values to account for the difference in length between the rod cell (8.76") and the homogeneous cell (8.625").
- (3) The values are the rod cell mass corrected by the ratio of the cross-sectional area occupied by the 12 groups of sheet material in the homogeneous cell to the area of a cell, i.e., $1.7894/1.90 = 0.941$. The masses listed for U, W and Ta are those used and agree with the required values within a gram.
- (4) Teflon was used to mockup the oxygen in the cell. The first set of values under 'homogeneous cell' are the oxygen masses corrected as described in (3) above, the second set of values are the required equivalent teflon masses to match the oxygen and the final set of values are the teflon masses used in the cell. The deficiency could not be corrected because the volume would not accommodate more teflon.

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86

Normalized Activity

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Figure 7.5
710 C. E. MOCKUP 1A
RELATIVE LONGITUDINAL POWER PROFILE

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-87-

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89

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-91-

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Figure 7.9
Relative Radial Power Profiles
Homogeneous Cell in 150
1, 7, 13 cm Locations

Figure 7. 10
Relative Radial Power Profiles
Homogeneous Cell in 150
17, 26, 36 cm Locations

TABLE 7.3

POWER DISTRIBUTION COMPARISON

<u>Measurement Description</u>	<u>Longitudinal Position (1)</u>	<u>Core-Edge Peak Power</u>	<u>Peak/Center⁽²⁾ Power Ratio</u>	<u>Center/Minimum Power Ratio</u>	<u>Minimum Location⁽³⁾</u>
	1	3.29 ⁽⁴⁾	4.94	1.22	4.0
X50 Radial	7	4.13	4.56	1.38	3.5
(Homogeneous	13	4.17	4.13	1.39	4.0
cell in 150)	17	4.14	4.14	1.40	4.0
	26	3.36	4.17	1.42	4.0
	36	1.17	4.11	1.31	4.0
	1	2.81 ⁽⁵⁾	4.30	1.24	4.0
X63 Radial	7	3.37	3.81	1.43	2.0
(Apex cell in 263	13	3.44	3.44	1.47	3.0
with no buffer zone)	17	3.51	3.49	1.46	2.0
	26	3.05	3.83 ^(?)	1.48	3.0
	36	1.43	5.06 ^(?)	1.36	4.0
	1	3.00	4.60		
X63 Radial	7	3.95	4.46		
(Apex cell in 563 for	13	4.03	4.03		
core eccentricity	17	4.03	4.01		
evaluation)	26	3.34	4.20		
	36	1.24	4.38		
	1	3.18	4.86	1.24	4.0
X63 Radial	7	3.84	4.33	1.43	2.5
(Apex cell in 163	13	3.95	3.95	1.44	3.0
with 1/2 hex homo.	17	3.87	3.85	1.46	2.5
buffer zones)	26	3.11	3.89	1.46	3.0
	36	1.25	4.37	1.36	3.5

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Table 7.3 (Cont'd)

<u>Measurement Description</u>	<u>Longitudinal Position (1)</u>	<u>Core-Edge Peak Power</u>	<u>Peak/Center⁽²⁾ Power Ratio</u>	<u>Center/Minimum Power Ratio</u>	<u>Minimum Location⁽³⁾</u>
X 63 Radial (Apex cell in 163 with teflon removed)	1	2.92	4.47		2.0 ± 0.5
	7	3.62	4.08		2.0 ± 0.5
	13	3.73	3.73		2.0 ± 0.5
	17	3.74	3.72		2.0 ± 0.5
	26	2.98	3.73		2.0 ± 0.5
	36	1.18	4.17		2.0 ± 0.5
X 63 Radial (Across core at table separation plane)	15.24	4.46 ⁽⁶⁾	3.68	1.43	3.0

- (1) Distance in centimeters from reflected end of core.
- (2) Where data for core center were not obtained during the exposure, the extrapolated value from the average normalizer band was used.
- (3) Distance in centimeters from the edge of core.
- (4) Values taken from exposure involving modified homogeneous cell with correct material masses in cell 150, Figures 7.9 and 7.10. The remainder of the radial power data from this measurement are those presented in Figures 7.6 through 7.8.
- (5) These data were obtained by exposing the apex cell in 263 and the remainder of the radial data obtained on a 30° radius to cell 163. The low peak values are believed to be attributed to the core eccentricity problem rather than normalization difficulties.
- (6) High value due to foil area integrating over region of higher thermal flux than normally present at core boundary when foil plane is parallel to the boundary.

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Figure 7.11 illustrates the resultant profile and Figure 7.12 is an exploded view of the same profile with the normalized values shown. These data have been normalized as the previous data to the foil 13 cm from the reflected end of the core located at the edge of cell 0. The following resultant parameters for the core power were derived from this profile:

Peak Power = 4.463

Peak/Center = 3.68

Center/Min. = 1.43

Location of Min. = 3.0 cm from edge of core

These values agree favorably with the cross-plotted radial data presented in the previous section.

7.1.3 Radial Profile Using Apex Cell

Subsequent to the completion of the measurements made along the X50 horizontal radius, it was decided that a radius extending from the core center out through the center of the X63 cell presented a more desirable geometry than did the radial through the X50 cell. This preference was based upon the marked difference at the outer boundary, where one-half of the X50 type cell extends beyond the adjacent core boundary while the X63 type cell is more uniformly located with respect to the surrounding cells. The geometry of the X63 type cell is enhanced in that respect if material is removed from the outer apex as shown in Figure 7.3. To provide a homogeneous array of materials a special cell, hereinafter called the apex cell, was assembled with sheet material. The material masses used in the apex cell are listed in Table 7.4 and compared to the normal rod masses. An aluminum spacer was placed in such a manner to confine the sheet material within a rectangular region and the inner most apex was filled with rod materials of approximately the same volume fraction as the normal cell loading. Catcher foils were distributed across the apex cell to obtain power spike definition. The radius from the core center to the outer edge of this modified apex cell was 21 cm (which was nearly the same as the horizontal radius of an equivalent cylinder having the same volume as the core).

Four different areas were investigated using the apex cell and they included the following:

1. Apex cell with no adjacent buffer zones.
2. Apex cell with one-half hex thick homogeneous type buffer zones on each side of the apex cell to evaluate the effect of the heterogeneous rod type surroundings.
3. Apex cell with all of the teflon sheets removed to evaluate the effect of oxygen.

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Normalized Activity

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-97-

Normalized Activity

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TABLE 7.4

APEX CELL COMPOSITION

<u>Material (1)</u>	<u>Table</u>	<u>Masses (grams)</u>		<u>Teflon Desired</u>	<u>Used</u>
		<u>Normal</u>	<u>Corrected (2)</u>		
Oralloy	M	714.0	476.3		488.1
	F	1042.5	684.9		698.7
Tungsten	M	878.6	586.0		583.3
	F	1263.5	842.7		848.4
Tantalum	M	94.7	63.1		63.1
	F	138.2	90.8		95.1
Oxygen	M	85.0	56.7	59.2 ⁽³⁾	46.0
	F	122.0	81.4	85.0	64.5

- (1) The thicknesses of the various materials used was as follows: U = 0.004", W = 0.005" and 0.010", Ta = 0.001" and 0.002", Teflon = 0.030". The width of the materials was 1.438".
- (2) Each of these values has been corrected for the reduced volume to be filled by sheet materials. The apex cell volume is 0.667 of the total hex volume. The fixed table values have been corrected by 0.985 to account for the difference in lengths, 8.625" for the apex cell to 8.76" for the normal rod cell.
- (3) Teflon sheets were used to mockup oxygen and these are the required equivalent masses of teflon for the oxygen based on equivalent flux-averaged scattering cross-sections. The deficiency shown in the "used" column could not be corrected because the region would not accommodate additional teflon sheets.

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4. Apex cell exposed in cell 563 to evaluate the eccentricity of the core with respect to the radial reflector. The mass of the core had displaced the core-structure such that the gap between the core and core shell was smaller at the bottom near cell 563.

Figures 7.13 and 7.14 present the data obtained using the apex cell without adjacent homogeneous buffer zones.

An exposure was made to determine the magnitude of the effect of the core eccentricity, which was caused by the weight of the material in the core, creating a distortion of the matrix and a slight longitudinal tilting of the core in each table toward the separation plane. Therefore, the lower core boundary was nearer the reflector than the upper core boundary by 0.175" in the movable table and 0.225" in the fixed table. The apex cell, without the buffer zones, was exposed in cell 563 and the data from this measurement are presented in Figures 7.15 and 7.16. If these data are compared with Figures 7.13 and 7.14 in which the apex cell was exposed in the diametrically opposite cell, i.e., cell 263, without the buffer zones, it indicates that the eccentricity causes an average increase in the magnitude of the power spike of approximately 13% at the bottom of the core. The one exception to this is the result at 36 cm from the reflected end of the core which shows the opposite effect. The longitudinal tilting of the matrix could cause this effect; however, since this is such an abrupt discontinuity in the effect as a function of longitudinal position, it is believed that this anomaly is the result of poor data at the 36 cm location. Figures 7.17 through 7.19 illustrate the radial data from catcher foil bands across the core and in the apex cell with a half-hex homogeneous buffer zone on each side of the apex cell. The presence of the buffer zone apparently increases the power peak 10% except near the open end. The location of the minimum and the center-to-minimum power ratio do not appear to be affected, however.

The data from the exposure to evaluate the effect of removing the teflon are presented in Figure 7.20 through 7.22. The teflon was used to mockup the oxygen in the apex cell and the adjacent buffer zones and the absence of the oxygen reduces the power peak approximately 6% and moves the location of the minimum power nearer to the core boundary.

7.1.4 Summary and Comments Related to Mockup 1A Power Distribution Comparisons

Table 7.3 summarizes the data obtained from the various power distribution measurements. Several of the measurements involved only the apex cell without catcher foil bands internal to the core apex cell along the radius. It was decided that the complete set of foil-bands was not necessary for each exposure after comparing several of the longitudinal profiles from bands at the same location exposed under different conditions. This comparison showed good agreement

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- 100 -

Figure 7.13
Relative Radial Power Profiles
Apex Cell in 263
1, 7, 13 cm Locations

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-101-

Distance from Outer Edge of Apex Cell (cm.)
No Buffer Zones

Figure 7.14
Relative Radial Power Profiles
Apex Cell in 263
17, 26, 36 cm Locations

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Normalized Activity

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-102

Figure 7.15
Relative Radial Power Profiles
Apex Cell in 563
1, 7, 13 cm Locations

Normalized Activity

Cell
563

7 cm. from Front Reflector

Normalized Activity

13 cm. from Front Reflector

Distance from Outer Edge of Apex Cell 563 (cm.)

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-103-

Figure 7.16
Relative Radial Power Profiles
Apex Cell in 563
17, 26, 36 cm Locations

Cell
563

Distance from Outer Edge of Apex Cell 563 (cm.)

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Figure 7.17
710 C. E. MOCKUP 1A
RELATIVE RADIAL POWER PROFILE
1 cm. from Front Reflector

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Figure 7.19

710 C. E. MOCKUP 1A
RELATIVE RADIAL POWER PROFILE
36 cm. from Front Reflector

Normalized Activity

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Distance from Outer Edge of Apex Cell 163 (cm)

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Normalized Activity

Distance from Outer Edge of Apex Cell 163 (cm)

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-109-
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Normalized Activity

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Distance from Outer Edge of Apex Cell 163 (cm)

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to exist out to the final hex layer of the core. One shortcoming of the apex cell is the difficulty associated with determining the location of the minimum power. This is due to the limited spread in the homogeneous dimension, 2.2 cm across which catcher foil bands can be positioned. This limit coupled with the difficulty in placing catcher foil bands along the 30° radius reduces the definition of the location of minimum power.

Though the power distribution nominally can be described by a typical radial profile and a typical longitudinal profile, the coupling between these profiles gives rise to two dimensional trends which are tabulated in Table 7.5 and described below:

1. The relative * power spike at the radial core edge is greatest near the reflected end of the core, and least near the longitudinal center of the core, the difference being approximately 20%. The relative power spike at the open end of the core appears to be enhanced a few percent, but the data is not quantitatively conclusive.
2. The gross radial power profile (exclusive of the spike) is flattest near the reflected end and most sloping near the longitudinal center, the difference being approximately 15% in the center to minimum power ratios. The open end of the core has a gross profile intermediate between these.
3. The longitudinal profiles show that the flux at the front (reflected) end of the core has the least reduction near the outer radius of the core. The longitudinal trends at the unreflected end do not vary much across the radius.
4. In general, the front extension to the radial reflector has a substantial effect on the power distribution in its vicinity, elevating the relative power in these regions.

10

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Relative to the center line power at that longitudinal location.

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TABLE 7.5

MOCKUP 1A

Ratio of Peak to End-of-Core Longitudinal Power

Unreflected

Position (1)	Peak Power	Power 1 cm from Reflected End of Core	Power 36 cm from Reflected End of Core	Relative Power Ratio	
				Peak Reflected End	Peak Unreflected End
0 (C)	1.011	0.669	0.290	1.511	3.486
0 (OE)	1.005	0.655	0.285	1.534	3.526
110 (C)	1.003	0.658	0.278	1.524	3.608
110 (OE)	0.972	0.641	0.271	1.516	3.587
120 (C)	0.950	0.628	0.265	1.513	3.585
120 (OE)	0.898	0.595	0.245	1.509	3.665
130 (C)	0.859	0.577	0.250	1.489	3.436
130 (OE)	0.805	0.562	0.235	1.432	3.426
140 (C)	0.746	0.523	0.224	1.426	3.330
140 (OE)	0.721	0.568	0.215	1.269	3.353
150 (OE)	4.10	3.18	1.10	1.289	3.727

(1) The cell positions listed are: (C) = Cell Center, and (OE) = Outside edge of cell or flat nearest radial reflector.

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7.2 Mockup 1C Power Distribution

The relative power distribution was measured in the Mockup assembly using the catcher foil technique employed on other assemblies and by exposing uranium-aluminum alloy wires. These wires, 0.020-inch in diameter with 9.6 w/o highly enriched uranium, were used as the means to measure the power distribution in fuel compacts which were assembled in lengths compatible with each longitudinal region of the core. These compacts had 37 evenly distributed holes, 0.081-inch diameter, which extended the full length of the core and into which wires were positioned to obtain radial and azimuthal power data. Measurements were made in the compact cells using small diameter fission probes to obtain relative power distribution data which could be compared to that obtained from the fueled wire.

The measurements were made to obtain data related to each of the following areas:

1. Gross radial power data from catcher foil bands inserted longitudinally at preselected radial locations.
2. Radial and azimuthal data in compacts from U-Al wires in SS tubes used to shield wires from fission products.
3. Radial and azimuthal data in compacts using Ta tubes in place of SS tubes.
4. Fine radial data in segmented compacts using 1/4-inch diameter catcher foils.
5. Fine radial data using catcher foils in the homogeneous and apex cells.
6. Radial and azimuthal data using small fission probes.

All of the above measurements included the gross longitudinal variations, with the greater emphasis on the reflected end of the core. Each of these areas is discussed in the following sections and the appropriate results displayed. In the case of the fueled wires, the data are presented in the form of isopower plots which are composites of all of the wire exposures.

7.2.1 Catcher Foil Measurements

The aluminum catcher foil technique of measuring the relative power distribution was employed in the 710 C.E. Mockup 1C assembly. The first measurement involved the use of an aluminum catcher foil tape placed across the core at the separation plane, 15.24 cm from the reflected end of the core. Foils, 1/4-inch in diameter, were punched on 1 cm centers and counted and the data normalized to the foil located

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at approximately the core center. Two exposures of this type were made to obtain the complete radial profile and the results are shown in Figure 7.23.

Additional full core length catcher foil bands were positioned at the outer flats of cells 0, 110, 120, 130, 140 and 150 to obtain relative radial power distribution data at various longitudinal positions. Normally, 1, 7, 13, 17, 26 and 36 cm from the reflected end of the core were used. Figure 7.24 illustrates a set of the longitudinal power profiles and Figures 7.25 and 7.26 show the cross-plotted radial data. These data are all normalized to the foil located 13 cm from the reflected end of the core at the hex-flat of cell 0.

Another previously used technique of measuring the fine radial power distribution at the core edge was the construction of special cells composed of equivalent masses of materials in sheet form to simulate a homogeneous region. Two such cells were assembled, one for cell 150 called the "homogeneous" cell and the other for cell 163 called the "apex" cell. Table 7.6 lists the material masses for each type of cell. In the "homogeneous" cell the sheet material and the catcher foils were oriented normal to the horizontal radius. In the "apex" cell, the outer apex was a void and again the sheet material and catcher foils were oriented normal to the 30° radius. Figures 7.29 and 7.30 show the radial data obtained from each of the cells described above. The void at the outer apex (See Figure 7.28) was created in order to make the length of the two radii equal; however, the difference in the core boundary between the "apex" cell and the complete compact with wires make a data comparison inappropriate. It is possible, however, to compare the sliced compact catcher foil results to the wire results in cell 163. Figure 7.35 presents these data, and indicates variations of the order of 10% were observed between the two sets of data. A more complete comparison is available using the results from cell 150 shown in Figure 7.36 which includes the "homogeneous" cell catcher foil results, sliced compact catcher foil results and wire results exposed in both stainless steel and tantalum tubes. Variations between the different measuring techniques are less than 10%, and randomly distributed in this set of data.

A section of the compacts, 1/2-inch in length, was assembled in layers which allowed the fine radial power distribution to be measured using 1/4-inch diameter catcher foils between layers. Figures 7.27 and 7.28 illustrate the sliced compact sections used. As shown in the figures, the catcher foil assembly used in the sliced compacts was composed of an aluminum strip to shield the aluminum catcher foil from the compact surface, the aluminum catcher foil and a strip of 0.001" thick fuel sheet. The construction of sliced compacts was such that the catcher foil radial locations matched rows of holes and hence wire locations in the regular compact assembly. Radial data showing the comparison of these catcher foils to wire results are presented in Figure 7.36.

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Figure 7.23

RELATIVE RADIAL POWER PROFILE
 Catcher Foil Tape Placed Between Table Halves
 Across Apex Cells
 (Cells 163 to 463)

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Figure 7.24
LONGITUDINAL POWER PROFILE
RUN 483
Catcher Foil Data

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Figure 7.26
RELATIVE RADIAL POWER PROFILE - TOTAL CORE
RUN 495
Catcher Foil Data

Normalized to Cell "0" - 13 cm from
reflected end of core.
Compacts in 140, 150, 151, 162

Distance from Center of Core (cm)
(Horizontally through Cell 150)

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TABLE 7.6

MASS EQUIVALENCES IN VARIOUS CELLS ⁽¹⁾

<u>Material</u>	<u>Mockup 1C Rod Cell</u>	<u>Compact Cell</u>	<u>Homogeneous Cell</u>	<u>Apex Cell ⁽⁵⁾</u>
Fuel - gms	2045.0	2083.0	2084.2	565.1
Tungsten - gms	2663.8 ⁽²⁾	2783.0	2150.2	583.3
Oxygen - gms	228.0 ⁽³⁾	288.0	296.1 ⁽⁴⁾	80.1

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- (1) The masses presented are for full core length cells except where noted.
- (2) Tungsten in both tungsten and tungsten oxide rods.
- (3) Oxygen in WO₃ rods.
- (4) Teflon sheet used to mockup oxygen, i.e., teflon mass = (1.042) (oxygen mass), as established by matching flux-averaged scattering cross sections.
- (5) These masses are for the 6" long movable table and the volume into which the sheet material was substituted was 0.67 of the total hex volume.

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U, W, and Teflon Sheets

"Homogeneous" Cell
(Exposed in 150-M)

Catcher Foil Assemblies (Al, Al, U)

Sliced Compact Section
(Exposed in 150-M
at 13 cm from reflected end of core)

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Movable Table
(Partial Core View)

Figure 7.27

SLICED COMPACT SECTION & SIMULATED HOMOGENEOUS CELL

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"Apex" Cell
(Exposed in 163-M)

Catcher Foil Assemblies (Al, Al, U)

Sliced Compact Section
(Exposed in 163-M
at 13 cm from reflected end of core)

Movable Table
(Partial Core View)
Figure 7.28

SLICED COMPACT SECTION & SIMULATED APEX CELL

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Figure 7.29
RELATIVE RADIAL POWER PROFILE

CELL 150 - RUN 510

Catcher Foil Data

Normalized to Cell "0" - 13 cm. from
reflected end of core.
Homogeneous Cell in 150

Normalized Activity

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Figure 7.30
RELATIVE RADIAL POWER PROFILE
CELL 163 - RUN 518
Catcher Foil Data

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Normalized Activity

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7.2.2 Uranium-Aluminum Wire Measurements

The Mockup 1C loading and reflector thickness had been adjusted so that the rod and sheet-type fuel sections would be approximately the same composition as the fueled unclad compacts. These compacts were similar to those intended to make up the regular 710 fuel elements and since the unclad coolant channels are only 0.081-inch diameter holes, the use of catcher foils as a means to measure the power was precluded. Therefore, there existed a need for developing a new technique, applicable to the small circular coolant channels. It was decided to use dilutely fueled aluminum wire of 0.020-inch diameter. The counting of the wires required the use of background (residual activity) corrections since each length of wire was to be reused numerous times. One of the tests was to compare the results obtained with the wires to those obtained with catcher foils.

The use of U-Al wire in the holes of the bare compacts required each wire to be inserted into a piece of tubing in order to eliminate the possibility of the wire "catching" spurious fission products from the surface of the compact. For the majority of the exposures, the tubing used was stainless steel; however, an exposure using tantalum tubes was made to determine the difference between the two materials in the Mockup 1C. This comparison indicates that little or no difference existed as shown in Figure 7.36.

The procedures related to wire handling and counting were developed and are presented here in brief form. Each length of wire was identified by a permanent number which related it to the original wire which had been "fingerprinted" by exposing it in a uniform thermal flux and counting it every centimeter over its entire length. A temporary number was added to the wire identification and was made compatible with a data reduction computer program and the identification which was manually programmed into the counting system during the wire counting.

In order to position the wires beneath the counting heads, each exposed wire was inserted into a piece of stainless steel tubing which was slotted at preselected locations. The slots were 1 cm in length and the center of the slot was aligned with the trapezoidal-shaped scintillation crystal of the counting system. Figure 7.37 illustrates the geometry of the crystal as well as the wire and holder assembly. The wires were scanned along their lengths in at least three different locations. Each wire was scanned three times and the average count computed by the data reduction program. Each location was counted against a preselected count on a wire exposed during the same exposure in cell 0. This method of correcting for decay was the same as utilized in counting catcher foils.

The wires were exposed in the holes of the outer cells of the core, i.e., 150, 151, 162 and 163. Exposures involving the use of wires in 140 and 152 were made to obtain better data definition. Figure 7.31

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South Edge
outside edge of Cell 150)

Fixed Table

Figure 7.31
Hole Identification Layout

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illustrates the compact hole identification used for this series of measurements. Figure 7.32 shows the complete longitudinal profile obtained using wires and the radial power in the compacts located in cell 150 are presented in Figure 7.33 and 7.34.

It was necessary to accept net deviations due to counting statistics and fuel wire non-uniformities of approximately $\pm 3\%$. The 9.0% U-235 by weight in the 0.020-inch diameter wire would not provide satisfactorily high fission product activity levels without making the exposures at excessively high power levels. Because of the poor counting statistics the data reduction program rejected counts which differed by more than 3 standard deviations from the average. Repeat exposures agreed quite favorably and the comparison of the normalized wire results to the fine radial data obtained using catcher foils are in excellent agreement.

The results of the wire counting are presented as isopower plots in Figures 7.38 and 7.39 for the 1 cm and 10 cm positions from the reflected end of the core. Each of these plots is normalized to cell 0; and the 10 cm plot was obtained by averaging the results from the 7 and 13 cm data, each of which had been normalized to their respective cell 0 position.

The power spike at the core edge was not present on the thinly reflected Mockup 1C and the gross radial power flattening provided by thicker reflected assemblies was not available as shown in Figures 7.1 and 7.23. Therefore, for this configuration the peak power parameter in column one of Table 7.7 is related to the core center value rather than the radial power peak of the Mockup 1A. This difference in the shape of the radial power profile between the Mockup 1C and the other configurations should be kept in mind while evaluating the two-dimensional trends of Table 7.7. The same general trend in the longitudinal distribution is observed near the reflected end as on the Mockup 1A, i.e., the power variation is less near the outer radius. A similar effect, however, also occurs at the unreflected end of the Mockup 1C, whereas such an effect was essentially non-existent in the Mockup 1A. This difference can probably be partially attributed to the effectiveness of the extended aluminum matrix as a rear reflector, an effect that was largely overwhelmed by the thick radial reflector of the Mockup 1A.

7.2.3 Fission Probe Measurements

ORTEC Model 781 Reactor Fission Probes were used to obtain relative power data in the compact cells to compare with U-Al wire data. A set of 4 such probes were used since they are sufficiently small (total outside diameter of 0.075-inch) to fit into the coolant holes. The probes are a pulse-type device, consisting of a surface barrier semiconductor charged particle detector with a U-235 fission foil mounted adjacent

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-125-

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Normalized Activity

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Figure 7.34
RELATIVE RADIAL POWER PROFILE
Cell 150 - Run 502
Wire Data

Normalized to Cell "0" - 13 cm from
reflected end of core.

Compacts in 150, 151, 162, 163
Wires in Ta Tubes during exposure

Distance from Reflected End

- - 13 cm
- △ - 7 cm
- - 1 cm

1.0

.8

.6

.4

.2

0

0

.5

1.0

1.5

2.0

2.5

3.0

3.5

Distance from Edge of Cell (cm)

Normalized Activity

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Figure 7.35

RELATIVE RADIAL POWER PROFILE

Cell 163 - 13 cm from Reflected End of Core

Normalized to Cell "0" - 13 cm from
reflected end of core

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U-Al Wire Counting Holders

U-Al Wire Counting Crystal

Figure 7.37

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-131-

Figure 7.38
 MOCKUP IC
 RELATIVE ISOPOWER PROFILE
 MEASURED IN HOMOGENEOUS COMPACT CELLS
 (1 cm from Reflected End of Core)

Figure 7.39

MOCKUP 1C
RELATIVE ISOPOWER PROFILE
MEASURED IN HOMOGENEOUS COMPACT CELLS
(10 cm from Reflected End of Core)

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TABLE 7.7

MOCKUP 1C

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RATIO OF PEAK TO END OF CORE LONGITUDINAL POWER

<u>Position</u>	<u>Peak Power</u>	<u>Power 1 cm From Reflected End of Core</u>	<u>Power 36 cm From Reflected End of Core</u>	<u>Relative Power Ratio</u>	
				<u>Peak Reflected End</u>	<u>Peak Unreflected End</u>
0	1.020	0.612	0.268	1.667	3.806
110	0.976	0.576	0.262	1.694	3.725
120	0.862	0.504	0.234	1.710	3.684
130	0.733	0.432	0.194	1.697	3.778
140	0.552	0.342	0.162	1.614	3.407
150 (1)	0.423	0.298	0.148	1.419	2.858
151 (1)	0.469	0.324	0.151	1.448	3.106
163 (1)	0.410	0.283	0.138	1.449	2.971
162 ()	0.409	0.286	0.134	1.430	3.052

(1) From surface facing toward reflector

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to the sensitive surface of the detector. The output pulse from the detector signifies a fission product depositing energy in the semiconductor. The probe is mounted on a type-304 stainless steel tube with a diameter of 0.062 inch. The fission foil which fits over the detector is electro-deposited U-235 on thin-walled stainless steel tubing, 0.075-inch OD. The foil is mounted to the detector with a suitable material to provide a water seal. All of the probes were made to the specifications listed in Table 7.8.

The use of the small fission probes required a calibration since the probes are not an absolute means of measuring the fission rate. For the calibration exposure runs, the probes were all bundled together and placed in the center of the core where the flux gradients are nearly zero. Counts were accumulated on all probes during a fixed interval of time and the relative calibration constant computed for each probe. The lowest counting probe was positioned in cell 0 at the normalizer position and the other three probes were placed at desired locations in holes of compacts. Data were obtained by exposing the probes and accumulating 1% statistics on the least sensitive probe. Exposures were made at three different longitudinal positions for two separate exposure series and the data appropriately normalized. The data for each of these series are presented in Table 7.9 and Figures 7.40 to 7.42. It should be noted that the second exposure series shows better agreement between the normalized wire and probe results than did the first and this is attributed to the care taken in calibration and positioning of the probes.

This technique development experiment was terminated prematurely so as to continue testing using established methods. Perhaps better agreement than the indicated $\pm 7.5\%$ standard deviations could be obtained if a more extensive series of measurements were made.

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TABLE 7.8

FISSION PROBE SPECIFICATIONS

Probe Sensitive Diameter	0.065 inch
Probe Sensitive Length	0.120 inch
U-235 Coating	$\geq 90^\circ$ enriched electroplated $\sim 1 \text{ mg/cm}^2$
Over-all Probe Length	4 feet
Thermal Neutron Sensitivity	$\sim 2 \times 10^{-4} \text{ c/neutrons/cm}^2$
Maximum Operating Temperature	100°C
Expected Life	5×10^{13} Fast Neutrons
	10^{12} Thermal Neutrons

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TABLE 7.9

FISSION PROBE AND WIRE COMPARISON

Mapped Hole	Longitudinal Distance ⁽¹⁾	Normalized Activity ⁽²⁾		Nw
		Probe	Wire	Np
		<u>First Exposure Series</u>		
163-14	1	0.259	0.253	0.977
	7	0.337	0.357	1.06
	13	0.299	0.369	1.235
163-44	1	0.259	0.298	1.15
	7	0.334	0.377	1.13
	13	0.415	0.424	1.02
163-65	1	0.264	0.326	1.235
	7	0.364	0.423	1.16
	13	0.515	0.503	0.977
				Avg. 1.105 ± 0.101
		<u>Second Exposure Series</u>		
150-44	1	0.318	0.278	0.874
	7	0.403	0.386	0.958
	13	0.468	0.452	0.987
151-44	1	0.317	0.336	1.060
	7	0.420	0.442	1.052
	13	0.469	0.528	1.126
162-44	1	0.271	0.257	0.948
	7	0.361	0.343	0.950
	13	0.400	0.391	0.978
				Avg. 0.993 ± 0.075

(1) Distance from reflected end of core.

(2) Normalized to position 13 cm from reflected end of core in cell 0.

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Figure 7.40

FISSION PROBE & WIRE COMPARISON

Longitudinal Data in Compact 163 - Hole 44

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Relative Activity

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Relative Activity

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Relative Activity

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7.3 Mockup 1D Power Distribution

Power distribution measurements were made radially and axially using both wires and catcher foils in the active core of the 710 Critical Experiment Reactor - Mockup 1D, thus defining in considerable detail the power distribution in the reactor. The majority of the measurements were accomplished using standard catcher foil techniques. However, aluminum-uranium wires were also used at the periphery of the reactor across the outer 4 typical cells (X50, X61, X62 and X63) to obtain fine resolution within the rod cells in areas of rapidly changing flux. Essentially, all of the measurements were confined to a 30 degree sector defined by the radii which extend from the core center, cell 0 to cells 150 and 163. Standard rod-type cells were normally used in the reactor except when obtaining detailed power profiles at the core boundary such as cells 150 and 163. Special cells (homogeneous and apex cells) were assembled using sheet materials with catcher foils sandwiched between the sheets of material to obtain detailed power at the core boundary. These cells were assembled in such a manner so as to have the plane of the catcher foils normal to their related radius, and had six catcher foil bands evenly spaced across the cell to define the power profile. Table 7.10 is a listing of the materials used in each of the special cells as well as the masses associated with the average rod-type cell used in the Mockup 1D.

7.3.1 Longitudinal Power Distribution

Two complete power distribution measurements were made to determine both the longitudinal and fine radial power distribution. The second measurement was essentially a repeat of the first and in addition, both the homogeneous and apex cells were placed in the movable table portion of the core to measure the detailed power at the core edge. The reduced data are presented in Figures 7.43 to 7.45.

The longitudinal profiles of Figure 7.43 show the axial power peak to occur at approximately 15 cm from the reflected end of the core. Exceptions are at the radial core boundary where the peak is shifted closer to the reflected end of the reactor as illustrated in Table 7.11 in which the ratio of the peak power to that at both ends of the core for all positions except the core boundary are given. It will be noted from this table and Figure 7.43 that there is a flattening of the longitudinal power distribution towards the outer radius of the reactor compared to that at the center. Since catcher foils could not be located precisely at the peak power point, the peak power values shown in Table 7.11 are those obtained from interpolation of the curves.

It was noted that when using the homogeneous cell in cell 150, the relative power at the outer edge of cell 140 and the outer edge of cell 150, both showed slightly lower relative power by approximately 7% than with the rod-type cell in 150. The homogeneous cell apparently

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TABLE 7.10

CELL LOADING COMPARISONS (masses in grams)

Material	Mockup 1D Rod Cell		Homogeneous Cell ⁽⁴⁾		Apex Cell ⁽⁵⁾	
	F.T. *	M.T. *	F.T.	M.T.	F. T.	M.T.
Oralloy	1091.7	748.6	1091.7	752.1	728.2	499.3
Tungsten	1457.7 ⁽¹⁾	999.7 ⁽¹⁾	1457.7	1002.1	972.3	662.6
Tantalum	165.5	113.5	165.5	125.7	110.4	74.9
Oxygen	140.4 ⁽²⁾	96.3 ⁽²⁾	146.3 ⁽³⁾	69.0	97.6	66.6

* F.T. means fixed table (8.76" length); M.T. means movable table (6" length).

- (1) These values are the sum of the tungsten from the W rods and WO₃ rods.
- (2) These values are related to the oxygen in WO₃.
- (3) Teflon was used as a substitute for oxygen in the special cells and the mass requirement calculated to be 1.042 times the oxygen mass.
- (4) Only the movable table section was used and the masses listed are those which made up the cell composition.
- (5) Only the movable table section was used and the masses are 0.667 of the rod cell requirement to account for the rectangular volume associated with this cell. The material masses listed are those used in the cell.

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Normalized Activity

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- 144 -

Normalized Activity

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Normalized Activity

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is more effective in stopping the low energy reflector flux from reaching cell 140 than the rod cell. The heterogeneity of the rod cell and the fact that moderating and scattering media (rods) are heterogeneously dispersed and are adjacent to the catcher foil bands within the cell probably is the cause of the power being slightly higher throughout the rod cell than in the homogeneous cell. For instance, at the outer surface of cell 150, "scattering" rods directly behind the catcher foil flux likely enhance the low-energy flux more than a homogeneous array of absorbing and scattering materials, which would quickly attenuate the flux incident from the reflector direction.

7.3.2 Radial Power Distribution

The radial power profiles were obtained by cross-plotting the data discussed in the previous section. The results from Run 599 are given in Figure 7.46 for the distribution from the center cell through cell 150 and Figure 7.47 for the distribution from the center through cell 163. The peak measured power is higher in each case by about 9% at the core edge on the outer surface of cell 150 than for cell 163 (see Figure 7.48). It should be noted, however, that the catcher foil band for cell 163 was not in the extreme corner of the cell, but essentially averaged the power along one of the outer flat surfaces. The flat surfaces of cell 163 do not see a full 2π solid angle of reflector flux, as does the outer surface of cell 150. The difference is even more pronounced for cell 151, whose outer surface sees even less of the reflector flux.

An over-all average radial profile was generated by normalizing the resultant areas under each longitudinal profile of Figures 7.43 to 7.45 to the area under the curve from cell 0, (using a planimeter). The resultant over-all radial profile is presented in Figure 7.48 and illustrates excellent agreement with the radial profiles at 13 cm of Figures 7.46, 47, 49 and 50, which are based on individual foil data and apparently are quite accurate. (Standard deviations from catcher foil data are nominally less than $\pm 2\%$). Note that the profiles for traverses toward cell 163 and 150 are identical, except near the core boundary where differences are caused principally by variations in the amount of reflector flux to which the foil was exposed.

The exposure of the homogeneous and apex cells in the reactor was performed only in the movable table and foils were punched at only three longitudinal positions on each tape, these being at 1, 7 and 13 cm from the reflected end of the reactor. The resulting radial power profiles at the three axial positions are given in Figures 7.49 and 50. Comparing the radial power profiles from the two runs for the "0" through "150" traverse (across flats) shows the same profile except in the homogeneous cell where the power is lower. This was pointed out in the previous section. That is, the power throughout the homogeneous cell was apparently lower by about 7% compared to the same distribution on the rod type cell. However, the direct comparison is only possible at the two flats, the only locations measured with the rod cell.

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As was mentioned before, data from the homogeneous and apex cells were obtained from the movable table only. Catcher foil data internal to the positions for the two special cells for Run 645 were from both tables. The radial power profiles for the fixed table (unreflected end) out to the location of the homogeneous cell and the apex cell are shown in Figures 7.51 & 7.52. The points at 9.9 cm on Figure 7.52 on the radial from cell 0 to 163 are all higher than for Run 599, as was observed in the movable table locations. A displacement or mislocation of the band is suspected, rather than a real effect in the power distribution. The remaining data compare very well for the two power distribution runs.

Considerable power distribution data were obtained near the radial core boundary using 20 mil diameter aluminum-uranium wire. The uranium content was 9% by weight and was 93.2% enriched. Comparisons of the wire and catcher foil data in cell 150 are shown in Figures 7.53 to 7.55. The catcher foil data are from the homogeneous cell measurement. It will be observed that catcher foil data were lower than the wire data, except for those wires directly behind uranium rods. This effect is obviously due to the heterogeneity of the rod-type cells.

The minimum radial power in all cases appears from 2 to 3 cm from the core boundary. The peak power at the edge of the reactor is a factor of about 1.6 above the core center near the axial midplane of the reactor. Further three-dimensional details of the power distribution are presented in Table 7.11.

7.3.3 Azimuthal Power Profile at Core Boundary

The U-Al wires were used to determine the relative power throughout the hex-shaped cross-section of the cells at the core boundary with the rod type cells in the reactor. From these data, isopower plots were made at 1, 7 and 13 cm, Figures 7.56 through 7.58. Included on these figures are the catcher foil data at the outer edge of the core. In some cases, the comparison between the two types of detectors at the core boundary does not appear to be too good; however, the catcher foil data measured an average effect over much of the outer flat, whereas the wire data were essentially point values (in the cross-section plane). The exact location of the wire within the triflute void between rods could significantly influence the flux that it receives. Experimentally, the catcher foil standard deviations averaged 1% to 2%, while the wire data standard deviations were in the range of 2% to 3%. Figure 7.59 was synthesized by averaging the 7 and 13 cm wire data and combining with internal catcher foil data to provide 10 cm data to compare with similar data obtained on the Mockup 1C assembly (Figure 7.39). The testing was terminated before repeat measurements could be made to resolve if these differences were physical (real) or due to experimental errors.

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TABLE 7.11

RATIO OF PEAK TO END OF CORE LONGITUDINAL
POWER - MOCKUP 1D

<u>Position</u>	<u>Peak Power</u>	<u>Power at Reflected End 1 cm</u>	<u>Power at Unreflected End</u>	<u>Peak/Reflected End</u>	<u>Peak/Unreflected End</u>
0	1.01	0.629	0.282	1.606	3.582
110	0.962	0.609	0.266	1.580	3.617
120	0.882	0.566	0.240	1.558	3.675
130	0.750	0.497	0.220	1.509	3.409
140	0.655	0.474	0.196	1.382	2.342
150	1.630	1.257	0.501	1.297	3.253
151	1.300	1.024	0.406	1.270	3.202
153	0.651	0.470	0.186	1.385	3.500
163	1.547	1.232	0.452	1.256	3.423
210	1.000	0.626	0.275	1.597	3.636
132	0.848	0.555	0.236	1.528	3.593
162*	1.650	1.303	0.491	1.266	3.360

* From surface facing directly towards reflector.

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Distance from Center of Core (cm)

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Figure 7.56

RELATIVE ISOPOWER PLOT* DERIVED FROM U-AL WIRES
(1 Centimeter from Reflected End of Core)

* Normalized to 13 cm. position on wire located in Cell O
The numbers in parenthesis are from catcher foils, placed across
outer surface.

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Figure 7.57

RELATIVE ISOPOWER PLOT* DERIVED FROM U-AL WIRES
(7 Centimeters from Reflected End of Core)

* Normalized to 13 cm. position on wire located in Cell O
The numbers in parenthesis are from catcher foils, placed across
outer surface.

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Figure 7.58

RELATIVE ISOPOWER PLOT* DERIVED FROM U-AL WIRES

(13 Centimeters from Reflected End of Core)

* Normalized to 13 cm. position on wire located in Cell O
The numbers in parenthesis are from catcher foils, placed across
outer surface.

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MOCKUP 1D
RELATIVE ISOPOWER PROFILE
MEASURED IN ROD-TYPE CELLS
(10 cm from Reflected End of Core)

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7.3.4 Power Distribution with Shield Next to Reflector

A variation of the basic 1D configuration involved surrounding the beryllium reflector with two hex layers of stainless steel followed by two hex layers of borated epoxy. In addition, the half-hex layer of stainless steel next to the beryllium was replaced by "heavimet" over a 180° sector. One power distribution measurement was made across the core in the region containing the heavy metal. Full core length longitudinal power profiles were obtained at three positions, cells 0, 530 and 550. These data are presented in Figure 7.60. A comparison of the peak power to the power at both ends of the core is listed in Table 7.12. The general shape of the longitudinal power distribution is no different from that of the configuration without the shield.

The radial profiles in the reflected end of the core are shown in Figure 7.61 as obtained from six catcher foil bands located across the core. The peak power at the core edge is approximately 25% higher than that without the added shield, illustrating the enhanced low energy flux created by the shield. (The worth of the shield was +1.29%Δk.) The shield also had the contrary desirable effect of flattening the gross radial power, reducing the center to minimum ratio by 12% and moving it away from the core edge from about 2.5 cm to about 3.5 cm.

7.3.5 Summary of Mockup 1D Power Distribution

Table 7.13 is a condensed summary of the two dimensional (radial longitudinal) power distribution trends on the Mockup 1D.

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* Heavy metal alloy consisting of 90% W by weight.

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TABLE 7.12

LONGITUDINAL POWER TRENDS WITH SHIELD

<u>Position</u>	<u>Peak Power</u>	<u>Power at Reflected End (1 cm)</u>	<u>Power at Unreflected End (36 cm)</u>	<u>Peak/Reflected End</u>	<u>Peak/Unreflected End</u>
0	1.020	0.633	0.280	1.61	3.64
530	0.803	0.534	0.227	1.50	3.54
550	2.570	1.668	0.674	1.54	3.81

TABLE 7.13

POWER DISTRIBUTION TRENDS - MOCKUP 1D

	<u>Radial Power Characteristic Longitudinal Position (1)</u>	<u>Peak Center</u>	<u>Center Minimum</u>	<u>Distance of Minimum From Edge</u>
Normal Configuration	1 cm	1.9	1.4	3 cm
	7	1.7	1.6	2-1/2
	13	1.6	1.6	2
	17	1.6 (2)	1.5	2
	26	1.6 (2)	1.5	2
	36	1.8 (2)	1.4	2
Shielded Configuration	1	2.6	1.2	5
	7	2.3	1.4	4
	13	2.0	1.4	3

(1) From the reflected end of the core.

(2) Rod-cell data. All other data is with "homogeneous cells" in the outer cells of the core. See discussion.

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7.4

SUMMARY AND CONCLUSIONS PERTAINING TO POWER
DISTRIBUTION MEASUREMENTS

The basic differences in the power distribution results for the three configurations with different reflector thicknesses are summarized in the introductory Section, 7.0. Figure 7.62 shows the basic trends in the power spike and gross radial power flattening as a function of the beryllium reflector thickness (with beryllium volume fraction of nominally 0.87).

Besides the general trends in the power distribution, a number of specific effects on the power distribution were discovered, as follows:

1. The eccentricity of the core within the circumference of the core shell and reflector was significant. An average difference of 0.2 inch in the width of the gap between the core and its shell resulted in a 13% difference in the magnitude of the power spike, with the spike being largest where the gap is smallest. The remaining portion of the radial power profile is unaffected by minor gap differences.
2. If oxygen (simulated as teflon) is removed from the outer cells, the power spike magnitude is reduced by approximately 6%.
3. When a "homogeneous" cell is substituted for a rod-type cell, the power spike is reduced approximately 7%. This latter effect appears to be not entirely consistent with item no. 2, above. However, the difference observed between the "homogeneous" and rod-type cells may be caused by an incorrect simulation of oxygen by teflon. The simulation was prescribed by a matching of total scattering cross sections.
4. When measurements are performed in a "homogeneous" cell, the magnitude of the power spike depends on the type of material in the adjacent cells. If the adjacent material is also homogeneous, instead of rod-type, the measured power spike is enhanced 8 to 12%, except near the unreflected end where the difference appears to be zero.
5. The boundary effects due to the unevenness of the outer boundary are significant. In the 1D reactor, with the moderately thick reflector, the power spike at the boundary is greatest for the cells (type 150) least shielded from the reflector. For a slightly jagged boundary such as cell 163 (see Figure 7.59), the power spike was 9% lower, and for a very jagged boundary (cell 151) the power spike was 20% lower than for cell 150.

In the case of the thinly-reflected Mockup 1C, where no power spike is evident, the power at the edge of cell 151 was 12% higher

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than at the edge of 150. This difference is probably not caused by the exposure to the reflector, but is the result of cell 151 being closer to the center of the reactor.

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POWER DISTRIBUTION VARIATIONS AS A FUNCTION OF BERYLLIUM REFLECTOR THICKNESS

FIGURE 7.62

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APPENDIX A

710 CRITICAL EXPERIMENT MOCKUP 1B

The 710 Mockup 1B Critical Experiment core loading was composed of five zones which were specified by computer calculations for the purpose of flattening the radial power profile. Figure A-1 illustrates the zonal loading used and lists the material volume fractions. In addition to the non-uniform loading, the initially loaded configuration had twelve evenly-spaced, reflector-length poison segments* located in the radial reflector as shown in Figure A-2. Other innovations associated with the Mockup 1B were reflector configurations composed of ten and twelve circular module mockups with poison segments used to mockup control drums of different radii as shown in Figures A-6 and A-12. The experimental efforts related to this assembly were the determinations of the reactivity effects associated with different poison control configurations, the reactivity worths of the poison segments as a function of angular position and the related effects on the power distribution.

The fully-loaded core of the mockup 1B had a k -excess of $0.192\% \Delta k$ with the poison segments rotated inward approximately 90° (position 2A of Figure A-3). An evaluation of the worth of the poison segments was made and showed that the excess reactivity of the fully-loaded core (208.3 kg of Orallo) with an unpoisoned reflector would have been $(3.04 \pm 0.1)\% \Delta k$. These results were obtained by two independent methods one of which was the evaluation of the summation of the k -excess with the poison segments in position 2A ($0.19\% \Delta k$), the worth of poison segment rotation from position 2A to position 1 ($2.15\% \Delta k$), and the worth of poison segment removal ($0.70\% \Delta k$). The second method involved the evaluation of equivalent safeties which were voids created by removing beryllium as the loading progressed and the poison segments were removed. This method showed the equivalent safeties to be worth $2.63 \pm 0.06\% \Delta k$ and the final k -excess of the system upon completion of the loading was $0.414\% \Delta k$ which produced $(3.04 \pm 0.1)\% \Delta k$ as the worth of the unpoisoned fully-loaded reactor.

The worth of the poison segment control system was determined using the reactivity changes produced by incrementally rotating a pair of the segments through approximately 180° from their outermost position, position 1, to position 5. The reactivity swing of the two poison segments, number 2 and number 3, was measured to be $0.990\% \Delta k$ which extrapolates to a control system worth of $5.94\% \Delta k$. Figure A-4 illustrates the integral worth shape curves as a function of angular position.

* Each poison segment was composed of a combination of three boron filled copper half-hex cans which were 10 inches long in the movable table and $8\frac{3}{4}$ inches long in the fixed table. The poison material was $97\% B_{10}$ (natural boron) and the average net weight of powder for each type was as follows:

AF-F = across flats, fixed table = 244.26 gms
AF-M = across flats, movable table = 265.87 gms
AC-F = across corners, fixed table = 250.09 gms
AC-M = across corners, movable table = 277.26 gms

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Power distribution measurements were made using the twelve equally spaced poison segments in a complete reflector. The poison segments were in position 2A which is at an average angular rotation of 80° from the fully out rotational orientation. A complete set of data was obtained to define the power distribution in each of the fourteen "typical" cells of sector 1. In addition, the power scallop at the core edge was measured using a circumferential catcher foil band positioned next to the core shell. The data for this series of measurements are presented in Tables A-1 through A-5. Tables A-1, A-2 and A-3 present the relative specific power (power per unit fuel mass) for ten of the "typical" cells, the data for the outer four "typical" cells being presented in Table A-5. Since the core had a five zone loading, the data of Table A-1 have been corrected for fuel mass differences to obtain the relative power density (power per unit volume) and are presented in Table A-4.

The data related to the circumferential band are shown in Figure A-5 and illustrate the presence of a scallop of approximately 20% in the proximity of the poison segments when rotated nominally 80° inward.

The additional power distribution measurement made using this reactor configuration was that in which poison segments No. 2 and No. 3 were rotated to their outermost position. These results presented in Table A-6 for the outer four cells show that the power spike at the core boundary is reduced by a factor of approximately 2 when the poison segments are rotated from the outermost to the 80° position.

No circumferential band exposure was made with the poison segments located in their outermost position; however, subsequent similar measurements on other configurations indicate that there is little or no power scallop present with the poison segments so far removed from the core.

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TWELVE CIRCULAR MODULE MOCKUP SYSTEM

The radial reflector arrangement used to mockup the twelve circular module system is shown in Figure A-6. Each module had 13 equivalent full hexagonal locations which provides approximately 13% more beryllium than would be required for a 2.95 inch radius reflector length drum, the desired configuration. The modules were created by removing beryllium from the inner and outer triflute regions and compensating for reactivity losses by the addition of fuel in place of tungsten rods uniformly throughout the core, as well as filling the equivalent safety voids which had been created during the poison segment removal from the complete reflector system. This reflector system resulted in a reactivity penalty of $(4.5 \pm 0.1)\% \Delta k$ compared to the complete, unpoisoned reflector system and required an additional 3.3 kg of fuel over the initially loaded 208.3 kg system with the drums at 80° . These values are referenced to an unpoisoned reflector module system. The poison segments were added later to two of the circular modules No. 2 and No. 3 to perform the reactivity worth as a function of angular position and power distribution measurements.

Modules No. 2 and No. 3 were rotated incrementally and the reactivity effects measured as a function of position. Figure A-7 illustrates the five positions used to measure the reactivity swing of the pair of modules and the resultant integral worth shape curve is presented in Figure A-8 for two natural boron poison segments. An extrapolation of these results indicate that the 12 circular module control system worth is $-5.203\% \Delta k$ and $-8.553\% \Delta k$ for natural and enriched poison segments,* respectively.

The power distribution of the 12-circular module system was measured with the poison segments at their outermost locations and again with them rotated inward 82° . The results presented in Figure A-9 show no scallop present at 0° and a flux depression of approximately 40% when rotated to position 3 (82°). A repeat of the measurement was made using 1/4-inch diameter foils to improve the resolution (compared to the standard 9/16-inch diameter foils) and the results were essentially identical.

Measurements made at the outer boundary of the outer cells showed that the power spike at the core edge is reduced approximately 25% when the segments were rotated from 0° to the 82° position. A comparative listing of these data are presented in Table A-7.

Since no scallop appeared between the poison segments when they were located in position 3, two additional exposures were made with the poison segments in position 4 (approximately 110°). The first of these was made with normal boron powder-filled segments and a scallop was present between the modules, although the effect appeared to be caused by greater flux depression near the poison segments rather than an enhancement of the flux between each module. The second exposure was made with enriched boron poison segments and these data show an additional depression; however, the general contours were the same, as shown in Figure A-10.

* The enriched boron poison segments were the same lengths and hex shape as were the natural boron poison segments; however, the boron powder was compacted to 1.15 gm/cm^3 and contained 84.1% B-10 by weight.

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TEN CIRCULAR MODULE MOCKUP SYSTEM

The ten circular module mockup system is presented in Figure A-12 and simulates a system of ten equally spaced circular modules each having a radius of 3.822 inches with the axes of each module being on a 13.09-inch radius from the core center. The volume of beryllium required was 18.9 hexagonals, each of which was 1.64 inches across flats. Therefore, the use of 19 equivalent full hex spaces were used to mockup the beryllium mass, except for the slight reduction in the over-all density created by the occasional use of half-hexes, safety bar hexes and specially milled hexes used to create a gap between certain modules.

The procedure used to obtain this reflector configuration was similar to that used for the creation of the twelve module system, i.e., the basic configuration shown in Figure A-11 had three equivalent safety voids present and as the triflute voids between modules were created, the reactivity compensation was accomplished by filling the equivalent safety locations with beryllium. Subsequent to filling the equivalent safeties, the zonal loading was altered slightly by replacing tungsten rods with fuel rods, as needed. This exchange was limited to one per cell working radially outward from the center of the core. An additional 2.56 kg of fuel was required over the initial 208.3 kg loading and the reactivity penalty associated with creating the ten module mockup system was $(4.1 \pm 0.1)\% \Delta k$ compared to the unpoisoned complete reflector system.

The reactivity worth of rotating two adjacent poison segments, No. 2 and No. 3, was measured using natural boron segments. The positions involved in the incremental rotation are illustrated in Figure A-13 and the integral worth shape curve is shown in Figure A-14.

A series of power distribution measurements was made to define the changes in the power distribution as a function of segment angular position. These data are presented in Figure A-15 and show the definite presence of a power scallop at every location except the outermost. One exposure was made at position 2 (88°) with enriched boron poison segments and produced the same general profile shape as had the natural boron segments; however, the magnitude was reduced approximately 5%.

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SUMMARY AND CONCLUSIONS OF MOCKUP 1B

A summary of the three measured Mockup 1B configurations and the extrapolated configuration of a complete and unpoisoned reflector is given in Table A-8. The control system worth that can be achieved with poison segments in a mockup control drum configuration was greater than $5\%\Delta k$, except in the 10 drum natural case when the result was $4.7\%\Delta k$. A slight modification in geometry could easily raise this above $5\%\Delta k$. A $2/3$ increase in control system worth was obtained by substituting enriched boron for the natural. This substitution was equivalent to increasing the amount of B-10 absorber by a factor of 4.5, all confined in the same volume.

The effect on the power spike at the edge of the core is summarized in Table A-9. It is obvious that the boron substantially reduces the magnitude of the power spike, and that the module systems have power spikes significantly lower than in the full-reflector configuration. Furthermore, scalloping of the power spike is generally not severe, as shown in Figures A-5, A-9, A-10 and A-15. Note, that in the latter three figures only two drums were in the desired position, and the edges of each graph show the unpoisoned reflector level. Table A-10 gives further information pertaining to the power scalloping of the gross radial power profile. It is apparent that the smoothest power distribution is achieved with the configuration having the most and the smallest drum modules.

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TABLE A-1

Normalized Catcher Foil Data for Specific Power
(power per unit fuel mass)

Longitudinal Position (1)	0 (2)	X10	Typical Cell (3) Outermost Flat		X40
			X20	X30	
1	0.617	0.593 ± 0.001	0.562 ± 0.006	0.513 ± 0.006	0.475 ± 0.004
7	0.875	0.848 ± 0.009	0.78 ± 0.002	0.690 ± 0.006	0.603 ± 0.002
13	1.0	0.973 ± 0.010	0.901 ± 0.014	0.794 ± 0.003	0.681 ± 0.003
17	1.014	0.975 ± 0.013	0.907 ± 0.008	0.793 ± 0.012	0.682 ± 0.015
26	0.272	0.269 ± 0.003	0.251 ± 0.004	0.217 ± 0.004	0.203 ± 0.003

- (1) The position is in centimeters from the reflected end of the core.
- (2) This is the normalizer band and the 13 cm location is that to which all foils were normalized.
- (3) These are the normalized catcher foil data for the foil bands located in each related cell. The standard deviations given were obtained from the results of the foils from the three radii shown in Figure A-2; i.e., X10 was derived from 110, 410 and 510, etc.

CONFIDENTIAL
-175-

CONFIDENTIAL

TABLE A-2

Normalized Catcher Foil Data for Internal Typical Cells
(power per unit fuel mass)

Longitudinal Position (1)	X21		X31		X41		X42		X52	
	110	121	131	142	141	143	142	153	141	152
1	0.593	0.576	0.565	0.527	0.486	0.535	0.527	0.474	0.486	0.464
7	0.841	0.805	0.787	0.722	0.641	0.730	0.722	0.637	0.641	0.576
13	0.962	0.915	0.912	0.824	0.733	0.832	0.824	0.718	0.733	0.638
17	0.961	0.917	0.903	0.824	0.729	0.828	0.824	0.728	0.729	0.644
26	0.766	0.728	0.719	0.658	0.590	0.658	0.658	0.590	0.590	0.506
36	0.259	0.253	0.246	0.230	0.206	0.226	0.230	0.212	0.206	0.184

(1) The position is in centimeters from the reflected end of the core.

(2) The data as listed are those used to obtain the cell center value, presented in Table A-4, for the typical cell of interest. The locations of each band are as shown in Figure A-2.

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TABLE A-3

Typical Cell Average Relative Specific Power Data ⁽¹⁾
(power per unit fuel mass)

Typical Cell ⁽²⁾	0	X10	X20	X30	X40	X21	X31	X41	X42	X52
Position ⁽³⁾ (cm)										
1	.620	.605	.577	.538	.495	.585	.546	.511	.501	.475
7	.885	.862	.814	.736	.647	.823	.754	.686	.680	.609
13	1.010	.987	.937	.848	.739	.939	.868	.783	.771	.686
17	1.025	.990	.941	.851	.739	.939	.864	.779	.776	.687
26	.812	.794	.754	.682	.594	.747	.689	.624	.624	.548
36	.276	.271	.260	.234	.210	.256	.239	.216	.221	.195

- (1) These data are the interpolated average throughout each typical cell obtained by averaging the catcher foil data on opposite sides of each cell (See Figure A-2). All data are normalized to the foil located at the edge of cell 0 (1.9 cm from the core center) at a longitudinal position 13 cm from the reflected end of the core.
- (2) The typical cells listed do not include X50, X51, X62 and X63. Since these cells are at the core edge and include the power spike, Table A-5 describes those results.
- (3) Longitudinal position in cm from the reflected end of core.

~~CONFIDENTIAL~~

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10
TABLE A-4

Typical Cell Relative Power Density Data⁽¹⁾
(power per unit volume)

Typical Cell	0	X10	X20	X30	X40	X21	X31	X41	X42	X52
Position (cm)										
1	.620	.605	.613	.605	.619	.585	.580	.607	.564	.594
7	.885	.862	.865	.828	.809	.823	.801	.815	.765	.761
13	1.010	.987	.996	.954	.924	.939	.922	.930	.867	.858
17	1.025	.990	.999	.957	.924	.939	.918	.925	.873	.859
26	.812	.794	.801	.767	.743	.747	.732	.741	.702	.685
36	.276	.271	.276	.263	.263	.256	.254	.257	.249	.244
Relative Cell Average	1.0	0.98	0.98	0.94	0.92	0.93	0.91	0.92	0.87	0.86

- (1) The power density correction was obtained by multiplying the data of Table A-3 by the fuel rods per cell associated with the cells from each zonal loading. The data as presented was normalized to Zone 1, the zone in which the normalizer band was located.

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TABLE A-5

Relative Specific Power Data ⁽¹⁾ of Core Edge Typical Cells

Typical Cell		X50	X51	X62	X63	Maximum Power Spike relative to edge of Cell 0	Maximum Power Spike in Mod. 1A
Position (cm)	Flat Location ⁽²⁾						
1	Edge	1.187	0.945	1.121	1.046	1.90	4.9
	Internal	0.471	0.480	0.458	0.453		
7	Edge	1.471	1.192	1.393	1.280	1.65	4.5
	Internal	0.605	0.614	0.576	0.565		
13	Edge	1.538	1.234	1.375	1.314	1.52	4.1
	Internal	0.679	0.706	0.639	0.636		
17	Edge	1.551	1.228	1.357	1.299	1.51	4.0
	Internal	0.670	0.703	0.637	0.634		
26	Edge	1.238	1.090	1.144	1.045	1.54	4.2
	Internal	0.531	0.557	0.510	0.514		
36	Edge	0.463	0.396	0.425	0.390	1.67	4.4
	Internal	0.199	0.197	0.191	0.190		

(1) The two values quoted are for the core edge and the internal flat for each cell involved. These data have been normalized to the foil located radially at the edge of cell 0 and longitudinally at 13 cm from the reflected end of the core.

(2) For the flat location, see Figure A-2.

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TABLE A-6

Normalized Activity Comparison in the Complete Reflector System
with Poison Segments at 0° and 80°

Longitudinal Position (cm)	Cell 150		Cell 151		Cell 162		Cell 163		Peak Core-Edge Power Cell "O" Power		
	0°	80°	0°	80°	0°	80°	0°	80°	1	2A	Mod. 1A, no drums
1	2.357	1.181	1.759	.945	2.313	1.121	2.086	1.046	3.8	1.90	4.9
7	3.056	1.456	2.274	1.192	3.024	1.393	2.643	1.280	3.5	1.65	4.5
13	3.092	1.532	2.254	1.234	2.850	1.375	2.711	1.314	3.1	1.52	4.1
17	2.995	1.547	2.235	1.228	2.914	1.357	2.665	1.299	2.9	1.51	4.0
26	2.417	1.238	1.859	1.090	2.521	1.144	2.128	1.045	3.1	1.54	4.2
36	.821	.462	.664	.396	.842	.425	.731	.390	3.1	1.67	4.4

CONFIDENTIAL
-180-

CONFIDENTIAL

TABLE A-7

Normalized Activity Comparison in the 12-Circular Module Mockup System
With Poison Segment at 0° and 82° (Position 3)

Long. Pos. cm from reflected end	Cell 150		Cell 130		Cell 140		Cell 150		Cell 151		Cell 162		Cell 163		Cell 154		Cell 250	
	0°	82°	0°	82°	0°	82°	0°	82°	0°	82°	0°	82°	0°	82°	0°	82°	0°	82°
1	.612	.603	.493	.475	.444	.414	1.319	.986	1.038	.746	1.334	.852	1.221	.768	1.034	.735	1.367	1.051
7	.859	.863	.669	.651	.551	.525	1.656	1.250	1.277	.910	1.685	1.035	1.495	.935	1.246	.877	1.650	1.253
13	1.0	1.0	.769	.735	.623	.605	1.642	1.269	1.281	.942	1.594	1.026	1.504	.962	1.264	.923	1.626	1.267
17	1.015	1.009	.756	.736	.620	.600	1.567	1.208	1.234	.932	1.510	.976	1.466	.922	1.224	.906	1.579	1.209
26	.802	.808	.590	.591	.500	.482	1.324	1.004	1.019	.754	1.342	.831	1.230	.768	1.013	.740	1.334	1.020
36	.266	.268	.216	.209	.179	.177	.545	.421	.418	.324	.525	.350	.459	.295	.460	.317	.583	.433

-181-

CONFIDENTIAL

CONFIDENTIAL

TABLE A-8

Characteristics of the Mockup 1B Configuration With a Zonal Loaded Core
Containing 208.3 Kg of Oralloid Metal

Configuration	K_{excess} (%Δk)	Equivalent Diameter of Drums (inches)	Number of Drums	Number of ⁽¹⁾ Poison Segments	Centerline Radius of Drums (inches)	Control System Worth (%Δk)	Type ⁽²⁾ of Poison
Full reflector no poison	3.0 ± 0.1	7.0	12				
Poison as in Fig. A-2	$+0.19 \pm 0.01$			36	13.4	5.94	Natural
10-drum, circular module	-1.12 ± 0.02	7.6	10	30	13.1	4.69	natural
		7.6	10	30	13.1	7.95	enriched
12-drum, circular module	-1.53 ± 0.02	6.7	12	36	13.2	5.10	natural
		6.7	12	36	13.2	8.55	enriched
Mockup 1A with uniformly loaded core containing 189.4 Kg of Oralloid Metal	-0.66 ± 0.03						

- (1) The poison segments were half hexes, 18.75 inches long, 0.82-inches (nominally half thickness across flats.
- (2) The natural segments were B₄C powder, compacted to 1.50 gm/cc, with 2% impurities. The enriched segments were boron powder compacted to 1.15 gm/cc, containing 84.1% of B-10, by weight.

CONFIDENTIAL
-182-

CONFIDENTIAL

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TABLE A-9

Power Spike at Core-Reflector Interface Relative to Center Cell of Core
(Longitudinal Midplane Values as Measured inside Tantalum Canister)

Basic Mockup 1A (no poison segments)	4.1
Basic Mockup 1B (poison segments outermost)	3.0
10-Drum Module (poison segments outermost)	1.9
12-Drum Module (poison segments outermost)	1.6
Basic Mockup 1B (poison segments at 80°) Max.value	1.5
10-Drum Module (poison segments at 88°) Max.value	1.5
12-Drum Module (poison segments at 82°) Max.value	1.3
12-Drum Module (poison segments at 110°) Max.value	1.1
12-Drum Module (enriched poison segments at 110°) Max. value	1.0

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TABLE A-10

10/11

Power Scallops Due to Control Drums
(as measured with circumferential band at core shell)

<u>Configuration</u>	<u>Nominal Drum Position</u>	<u>Type of Poison</u>	<u>Nominal Be Thickness Between Core and Poison</u>	<u>Minimum Power to Peak Power Ratio in Poison Drum Region</u>
Basic 1B	80°	natural	1.7 inches	0.94
Full Reflector			1.0 inches	0.84
10-Drum	88°	natural	3.5 (void)*	0.91
Modules			1.0 (void)*	0.69
12-Drum	82°	natural	1.1	1.0
Modules			1.0	1.0

* - Void implies that there is a direct or nearly direct steaming path between the poison segment and the core, and that the poison is only partially separated from the core by the beryllium thicknesses shown.

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FIGURE A-1

Zonal Locations

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~~CONFIDENTIAL~~
-180

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- Shim Actuators
- Safety Actuators
- Control Drums
(Boron filled
copper cans)

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Figure A-2
Twelve Poison Segments in a
Complete Reflector System
(Normal Catcher Foil Locations Shown)

CONFIDENTIAL
187

CONFIDENTIAL

Figure A-3
Poison Segment Rotational Positions
in the Complete Reflector System

CONFIDENTIAL
-188-

CONFIDENTIAL

CONFIDENTIAL
-189
Normalized Activity

CONFIDENTIAL

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Figure A-6
Reflector Configuration for the
Twelve Circular Module Mockup System

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CONFIDENTIAL
-191-

CONFIDENTIAL

Figure A-7
Poison Segment Rotational Positions
in the
Twelve Circular Module Mockup System

Figure A-8

710 C. E. Mockup 1B

Poison Segment Integrated Worth*
vs
Angular Position

*Rotation of two adjacent poison segments in the
12-circular module mockup system

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Integral Worth (%Δk)

CONFIDENTIAL

CONFIDENTIAL
-193-

CONFIDENTIAL

CONFIDENTIAL
-104

CONFIDENTIAL

Figure A-10
710 C. E. Mockup 1B
Circumferential Catcher Foil Profile
12-Circular Module Mockup System

10/11

CONFIDENTIAL
-195-

CONFIDENTIAL

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Figure A-11
710 C.E. Mockup 1B with
Equivalent Safeties Removed

CONFIDENTIAL
196-

CONFIDENTIAL

FIXED TABLE

FIGURE A 12

Reflector Configuration for the 10-Circular Module Mockup System

CONFIDENTIAL

197

Figure A-13
Poison Segment Rotational Positions
in the
Ten Circular Module Mockup System
(Facing Fixed Table)

CONFIDENTIAL

CONFIDENTIAL
-198-
Integral Worth (%Δk)

1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

Figure A-14
710 C. E. Mockup 1B
Poison Segment Integrated Worth
vs
Angular Position

Rotation of two poison segments in the
10-poison segment circular module
system

0 30 60 90 120 150 180

Position of Poison Segment from Outermost Location (degrees)

CONFIDENTIAL

~~CONFIDENTIAL~~
-199-
Normalized Activity

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