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ARMY GAS-COOLED REACTOR SYSTEMS PROGRAM

SUMMARY OF NUCLEAR PHYSICS EXPERIMENTS

MASTER

January 1965

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AEROJET-GENERAL NUCLEONICS

SAN RAMON, CALIFORNIA

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ARMY GAS-COOLED REACTOR SYSTEMS PROGRAM

SUMMARY OF NUCLEAR PHYSICS EXPERIMENTS

by

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ARMY GAS-COOLED REACTOR SYSTEMS PROGRAM

SUMMARY OF NUCLEAR PHYSICS EXPERIMENTS

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ARMY GAS-COOLED REACTOR SYSTEMS PROGRAM

SUMMARY OF NUCLEAR PHYSICS EXPERIMENTS

I. INTRODUCTION

Studies at the Oak Ridge School of Reactor Technology (ORSORT) in 1954, and by the Sanderson-Porter Co. in 1955 established the feasibility of the development of a mobile nuclear power plant for military use. The Army Gas-Cooled Reactor Systems Program (AGCRSP) was initiated in 1956 to develop such a power plant. Two nuclear reactors were built and operated under this program:

- The GCRE-I experimental reactor to provide core and fuel element information for the design of a demonstration power plant.
- The ML-1 demonstration power plant.

Nuclear experiments were performed with critical assemblies at Battelle Memorial Institute (BMI), in the GCRE-I reactor, and in the ML-1 reactor. The results of this work were documented in a number of reports which provide detailed discussions of the experiments and the various aspects of the developmental work performed; this report briefly summarizes the entire program of critical experiments.

The critical experiments began in 1957 with the construction of the GCRE Critical Assembly at BMI. The experimental work with this assembly began in the early part of 1958 and was completed in December of that same year. The assembly incorporated concentric tube-type fuel elements; the following measurements were made:

- Critical core configuration and worth of a peripheral element
- Worth of burnable poison
- Relative worth of lead and water radial reflectors
- Worth of flooded fuel elements (gas passages filled with water)
- Worth of fuel additions
- Worth of stainless steel additions
- Worth of non-uniform fuel element spacing
- Worth of various control-blade configurations and materials
- Worth of end reflector
- Values of temperature and void coefficients
- Flux and power distributions

The data obtained were used in the design of the GCRE-I reactor.

Two additional critical assemblies were utilized to develop the neutronic data for the ML-1 design. The first of these, designated the ML-1-IA Critical Assembly, incorporated concentric tube-type fuel elements and was operated in the GCRE critical assembly facility. The experiments with this assembly, which began in 1959, provided the data necessary to evaluate the following:

- Critical core configuration and worth of a peripheral element
- Worth of the ML-1-IA control blades
- Values of temperature and void coefficients
- Flux and power distributions

The second critical assembly was designated ML-1-IB and incorporated pin-type fuel elements. Experiments with this assembly provided data on:

- Critical core configuration and worth of a peripheral element
- Worth of ML-1 type control blades
- Values of temperature coefficients
- Flux and power distributions
- Flux and power depressions around control blades.

Experiments were performed in 1960 and 1961 with the GCRE-I reactor to substantiate GCRE-I design data and to provide data not obtained from the criti-

cal assemblies. The final portion of the ML-1 experimental physics program was accomplished in 1961 and 1962 at NRTS, with the ML-1 reactor. The following measurements were made:

- Critical core configuration and worth of a peripheral element
- Worth of control blades
- Values of temperature coefficients
- Axial and radial power distributions
- Effects of the control blades on power distribution
- Pin-to-pin power ratios in elements of various core loadings and for various pin sizes
- Worths of various reactivity shims
- Worths of several types of burnable poisons.

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II. DESCRIPTION OF CRITICAL ASSEMBLIES AND REACTOR CORES

Five basic systems were used in the AGCRSP nuclear physics experiments; the GCRE Critical Assembly, the GCRE-I Reactor, and ML-1-IA Critical Assembly, the ML-1-IB Critical Assembly, and the ML-1 Reactor. The five systems are neutronically similar; all are heterogeneous, water-moderated cores fueled with fully enriched uranium. The fuel is contained in elements suspended vertically in pressure tubes. The moderator water which surrounds the pressure tubes comprises about 50% of the core volume. The characteristics of the various fuel elements are listed in Table 1.

A. GCRE CRITICAL ASSEMBLY

The GCRE critical assembly (Figure 1) was built at the Battelle Critical Assembly Laboratory (Ref. a)*. The critical-assembly stand had three working levels; the floor level for the dump tanks, filling pump, and heating units; the core level for the reactor core and instruments; and the upper level for the critical-assembly control-rod drive units. The internal core structure is shown in Figure 2.

The core of the GCRE critical assembly consisted of a mocked-up gas plenum, fuel elements, support structure, control elements, and moderator water, all contained within the reactor tank. Two separate sets of control rods were provided. The critical-assembly control blades were inserted from the top of the core; these blades were calibrated and were used to determine reactivity changes throughout the experiment. The other set of control blades consisted of mockups of the control blades proposed for the GCRE-I reactor and could not be moved remotely. The mockup blades were installed to evaluate the control system designed for the GCRE-I reactor.

The pressure tubes and tube sheets were fabricated of aluminum; the fuel element spacing in one tube sheet was uniform (Figure 3), in the other tube sheet, the spacing was non-uniform (Figure 4). The non-uniform spacing was used to evaluate the affect of this approach in flattening the radial power profile; this core was referred to as the Uniform Radial Distribution Code (URDC).

*The reference list will be found immediately after the main body of text. Alphabetical designations refer to reports generally available, numerical designations to in-contract reports.

TABLE 1 - FUEL ELEMENTS USED IN THE EXPERIMENTAL PROGRAM

Parameter	GCRC	GCRC-I Reactor		ML-1-IA	ML-1-IB	ML-1 Reactor
	Critical Tube-Type	Plate Core (1Z)	Pin Core(a,b) (IB-2L)	Critical (Tube)	Critical (Pin)	
Active core length, in.	28	28	22	28	22	22
Pressure tube material	Al-6061	Al-6061	SS-321	SS-321	SS-321	SS-321
ID, in.	1.859	1.759	1.760	1.764	1.764	1.750
OD, in.	1.975	1.875	1.800	1.804	1.804	1.790
Outer liner material	SS-321	Zr	SS-316	SS-321	none	SS-316
ID, in.	1.480	1.660	1.720	1.480	-	1.668
OD, in.	1.500	1.720	1.750	1.500	-	1.688
Inner liner material	Al-6061	SS-316	SS-316	Al-6061	SS-347	Hastelloy X
ID, in.	1.305	1.406	1.426	1.305	1.476	1.426
OD, in.	1.375	1.426	1.446	1.375	1.500	1.446
Fuel material	U foil	UO ₂	UO ₂ (c)	U foil	UO ₂	UO ₂ (c)
Fuel element loading, gm U-235	303.39	315.01	810.0	303.39	646.91	810.0
Fuel tube/plate loading, gm U-235						
Inner tube/plate	48.54	50.40	-	48.54	-	-
Second tube/plate	67.05	69.62	-	67.05	-	-
Third tube/plate	84.04	87.26	-	84.04	-	-
Outer tube/plate	103.76	107.73	-	103.76	-	-
Fuel pin loading, gm U-235						
Inner pins	-	-	75.0	-	58.85	75.0
Outer pins	-	-	30.0	-	19.58	30.0
Burnable poison, gm/element	0.13 Cd(d)	0.163 Sm(b)	0.4 Cd(a)	0.13 Cd(d)	0.23 Cd(a)	0.4 Cd(a)

(a) Eleven in. long sheet of poison with 1 in. at each end feathered (see Figure 12)

(b) Six in. long section, located at the bottom of the fuel zone

(c) Inner pins, UO₂; outer pins, BeO-UO₂; center pin, Haynes 25 in IB-2L; Hastelloy X in ML-1

(d) Burnable poison is 5 in. long centered 15 in. above the bottom of the fuel

FIGURE 1. GCRE CRITICAL ASSEMBLY SHOWING MAJOR COMPONENTS

11.2-64-4116

FIGURE 2. GCRE CRITICAL ASSEMBLY CORE STRUCTURE

FIGURE 3. GCRE CRITICAL ASSEMBLY CORE NOMENCLATURE

Fuel element position numbers are given. Critical assembly control rod positions are denoted by numbers at the appropriate locations between fuel elements. Flux- and power-distribution measurements were made along radii AA and BB.

X-Y COORDINATES FOR SYMMETRY SECTOR					
ELEMENT POSITION	COORDINATES, inches		ELEMENT POSITION	COORDINATES, inches	
	X	Y		X	Y
1	0	0	13	3.52	2.03
5	2.35	0	28	6.18	2.19
14	4.70	0	48	7.80	4.50
29	7.20	0	48-DISPLACED	7.60	4.39
50	10.00	0	49	9.00	2.29
50-DISPLACED	9.77	0	49-DISPLACED	8.68	2.21

FIGURE 4. FUEL ELEMENT LATTICE SPACING FOR UNIFORM RADIAL POWER DISTRIBUTION CORE IN THE GCRE CRITICAL ASSEMBLY

The fuel element used in the GCRE critical assembly consisted of four concentric stainless steel tubes. The fuel, in the form of enriched-uranium foil, was taped to each of the tubes (Figure 5). The element was placed into a fuel-element container consisting of an inner liner, an outer liner, and a pressure tube. (An element of this design is henceforth referred to as a tube-type element.) When an element was removed from the core, the pressure tube was also removed and the space so vacated filled with moderator water.

B. GCRE-I REACTOR CORE

The GCRE-I reactor (Figure 6) was designed and built by Aerojet at the National Reactor Test Station (NRTS), Idaho Falls, Idaho (Ref. b). The reactor consisted of a core structure, moderator (pool water) and fuel elements. The core structure included the pressure tubes and tube sheets, the lead reflector, and other mechanical components (Figure 7). The reactor was controlled by 12 horizontal control blades.

Two types of fuel elements were provided for the GCRE-I reactor; a plate-type element, designated IZ, and a pin-type element, designated IB-2L.

The IZ element consisted of 315 ± 5 gm of fully enriched UO_2 dispersed in AISI Type 316 stainless steel to form a 0.033 in. thick "meat" section of 30 wt% UO_2 . The meat was clad with 0.006 in. of AISI Type 318 stainless steel. The plates were formed into 120° sections of right circular cylinder and assembled into four concentric cylinders as shown in Figure 8. The active length of the fuel plate assembly was 28 in.

The IB-2L fuel element consisted of an array of metal clad fuel pellets in an insulation package similar to that used in the IZ design. The fuel was fully enriched UO_2 . This material was cold-pressed and sintered to about 96% of theoretical density for loading in six of the fuel pins. The fuel pellets for the remaining 12 fuel pins (the central pin in the 19 pin array was unfueled) were fabricated from a mixture of 70 wt% UO_2 and 30 wt% BeO . The fuel pellets were loaded into Hastelloy X tubing which was fitted with top and bottom closure plugs. The 18 loaded fuel pins were arranged in two concentric rings about the unloaded central pin to form the fuel pin array. The active length in the IB-2L element was 22 in.; this dimension conformed to the core length in the ML-1 reactor and required that a 6 in. length of cadmium poison be installed in the bottom of the IB-2L elements to accommodate the element to the 30 in. tube sheet spacing of the GCRE-I reactor. The configuration of the IB-2L element is shown in Figure 9.

C. ML-1A CRITICAL ASSEMBLY

The ML-1-IA critical assembly (Figures 10 and 11) was identical to the GCRE critical assembly except that the tube sheets and pressure tubes were made of steel instead of aluminum (Ref. c).

D. ML-1-IB CRITICAL ASSEMBLY

The ML-1-IB was designed to simulate the ML-1 reactor (Ref. d).

FIGURE 5. GCRE CRITICAL ASSEMBLY TUBE-TYPE FUEL ELEMENT
 Burnable poison not shown

1. Reactor Support Stand
2. Reactor (Inlet Plenum)
3. Lead Reflector
4. Rod Guide Assembly
5. Stand Support Rods
6. Stand Safety Supports
7. Inlet Coolant Gas Duct
8. Outlet Coolant Gas Duct
9. Rod Actuator (Typ)
10. Rod Absorber Blade (Typ)
11. Neutron Detector (Typ)

FIGURE 6. GCRE-I REACTOR ASSEMBLY

FIGURE 7. GCRE-I CORE STRUCTURE

11.2-64-4121

FIGURE 8. GCRE-IZ PLATE-TYPE FUEL ELEMENT

FIGURE 9. GCRE-IB-2L PIN-TYPE FUEL ELEMENT

X-Y COORDINATES FOR SYMMETRY SECTOR					
ELEMENT POSITION	COORDINATES, inches		ELEMENT POSITION	COORDINATES, inches	
	X	Y		X	Y
1	0	0	28	6.158	2.06
5	2.375	0	49	9.095	1.955
14	4.75	0	12	2.375	4.12
29	7.388	0.025	27	4.999	4.07
50	10.173	-0.299	48	7.845	3.97
4	1.188	2.06	26	3.673	6.415
13	3.563	2.06	47	6.548	6.515
			46	5.345	8.660

FIGURE 10. ML-1-IA CORE LAYOUT

Dimensions in inches

FIGURE 11. ML-1-IA TUBE-TYPE FUEL ELEMENT
Burnable poison not shown

Fuel element configuration and fuel element spacing were the same as in the final ML-1 core design. A 0.0035 in. thick cadmium burnable poison foil was incorporated as shown in Figure 12; the poison was installed inside the outer liner. Six ML-1 type control blades could be inserted into the core and reactivity shims (0.028-in.-thick stainless steel) were wrapped on the outside of the insulation liner. The core layout is shown in Figure 13 and the core structure in Figure 14.

Two kinds of fuel were used in the ML-1-IB critical assembly; some elements used pelleted fuel exclusively while others are loaded with pelleted and powdered fuel. Both kinds of elements had equivalent fuel loadings and identical fuel (i.e., sintered fuel pellets) in the inner seven fuel pins. The fuel elements with pelleted fuel only had green (unsintered) fuel pellets in the outer 12 fuel pins; the other elements used U^{235} powder in the outer 12 pins. The powder was compacted to give the required U^{235} loading. The cladding in all the elements was identical.

E. ML-1 CORE

The ML-1 core (Ref. e) consists of 61 non-uniformly spaced fuel elements in a hexagonal configuration (Figure 15). Each element is surrounded by moderator water and the core is surrounded by a lead radial reflector. Each fuel element consists of 18 fuel pins concentrically arranged around an unfueled center pin (Table 1). The distance between the tube sheets is 24 in., and the fueled portion of the fuel elements is 22 in. long; this arrangement provides a 2-in. water reflector above the fuel. The fuel element spacing is identical to the ML-1-IB critical assembly (Figure 13). Initially, each element (Figure 16) included 0.4 g of cadmium burnable poison which was positioned next to the inner liner and "covering" the entire fueled region as in the ML-1-IB critical assembly (Figure 14). However, the poison was repositioned to the lower 11 in. of the fueled area at the time of final design of the ML-1-I fuel elements.

Three types of reactivity shims were provided for use with the ML-1 core; stainless, light silver, and heavy silver. The stainless steel shims were 0.010 in. thick stainless steel tubes 24 in. long. The light silver shims were made of stainless steel shims with the lower 12 in. plated on both surfaces with a 0.00175 in. layer of silver. The heavy silver shims were similar to the light silver shims except that the plating was 0.005 in. thick. The shims were used to maintain the desired excess reactivity in the ML-1 core loading.

FIGURE 12. CONFIGURATION OF COOPER-CADMIUM BURNABLE POISON IN THE ML-1-IB CRITICAL ASSEMBLY

11.2-64-4124

X-Y COORDINATES FOR SYMMETRY SECTOR					
ELEMENT POSITION	COORDINATES, inches		ELEMENT POSITION	COORDINATES, inches	
	X	Y		X	Y
1	0	0	27	4.999	4.07
4	1.188	2.06	28	6.158	2.06
5	2.375	0	29	7.388	0.025
12	2.375	4.12	47	6.548	6.515
13	3.563	2.06	48	7.845	3.97
14	4.75	0	49	9.095	1.955
26	3.673	6.415	50	10.173	-0.299

FIGURE 13. ML-1-IB CORE LAYOUT AND FUEL ELEMENT SPACING

112-64-4127

Plan View

Section A-A

Dimensions in inches

FIGURE 14. ML-1-IB CRITICAL ASSEMBLY CORE STRUCTURE

11-2-64-4128

FIGURE 15. ML-1 REACTOR CROSS SECTION

FIGURE 16. ML-1-I FUEL ELEMENT

III. EXPERIMENTAL DETERMINATIONS

A. CRITICALITY AND PERIPHERAL ELEMENT WORTHS

The criticality changes resulting from changes in configuration and component materials were determined for each of the five systems previously described. Twenty-five critical experiments were performed; 9 with the GCRE critical assembly, 6 with the GCRE-I reactor, 1 with the ML-1-IA critical assembly, 3 with the ML-1-IB, and 6 with the ML-1 reactor. The experiments are discussed in the following paragraphs and Table 2 provides a summary of the criticality data obtained.

1. GCRE Critical Assembly

A detailed description of the GCRE critical assembly experiments is given in References a and f.

a. Experimental Core

The experimental core used an aluminum tube sheet and a 2 in. water reflector (Table 1), but no burnable poison. The core went critical with 54 elements. The critical configuration and peripheral element worths are shown in Figure 17.

b. Clean Core

The clean core was identical to the experimental core except that all elements incorporated burnable poison. This core went critical with 64 elements in the configuration shown in Figure 18.

c. Pb-1 Core

The Pb-1 core was a clean 51-element core which was surrounded by a 4 in. thick lead reflector (Figure 19). The core went critical when the burnable poison was removed from four elements.

TABLE 2 - SUMMARY OF EXPERIMENTAL CRITICALITY DATA

Reactor	Core	No. of Elements	Core Loading, kg U-235	Excess Reactivity, % Δ K/K	Peripheral Element Worth, % Δ K/K	Figure No.*	Comments
GCRE Critical Assembly	Experimental	54	16.4	0.25	0.35	17	No burnable poison
	Clean	64	19.5	0.26	0.22	18	Cadmium burnable poison in all elements
	Pb-1	51	15.6	0.05	-	19	No burnable poison on four elements
	Pb-2	55	16.8	0.28	0.40**	20	Reflector distance varies from 1/8 in. to 3/4 in. from core
	Pb-3	56	17.1	0.50	0.39	21	Reflector distance 1/2 in. from core
	Flooded Pb-3	37	11.3	0.0	0.41**	22	Mineral oil used to simulate water in flooding
	Pb-3 with higher fuel loading	47	19.0	0.38	0.50**	23	Element loading 404 gm U-235
	Pb-3 with higher stainless steel content	58	17.7	0.08	0.37	24	0.050 in. thick stainless steel fuel element tubes
	Uniform radial power core	57	17.4	0.14	-	25	Non-uniform spacing
GCRE-I Reactor	Dry IZ	59	18.4	-	-	26	Aluminum tube bundle
	Flooded IZ	36	11.3	0.1	-	27	Aluminum tube bundle
	Dry IZ	66	20.6	0	-	28	Stainless steel tube bundle
	Flooded IZ	52	16.3	0.45	-	29	Stainless steel tube bundle
	Dry IB-2L	54	43.4	-	0.46	30	Stainless steel tube bundle
	Flooded IB-2L	45	36.1	-	-	31	Stainless steel tube bundle
ML-1-IA Critical	IA-Core	59	17.9	0.38	0.46	32	Concentric tube type core
ML-1-IB Critical	Dry, no shims	48	31.1	0.75	-	33	
	Dry, steel shims	51	33.0	0.42	0.45**	34	Steel shims
	Flooded, steel shims	42	27.2	0.44	0.5**	35	Steel shims
ML-1 Reactor	Dry, no shims	48	38.9			36	
	Dry, stainless steel shims	49	39.7			37	
	Dry, light silver shims	55	44.6			38	
	Flooded, no shims	35	28.4	0.8	0.60	39	
	Flooded, stainless steel shims	37	30.0	1.0	-	40	
	Flooded, light silver shims	48	38.9	0.9	0.28**	41	

* Note: Figures will be found immediately following citation in text.

**Average value

Note: Peripheral element worths ($\% \Delta K/K$) in position 44 and 57 obtained by measuring combined effect and distributing equally

- ELEMENTS THAT MADE UP CRITICAL CONFIGURATION
- NOT IN CRITICAL CONFIGURATION
- WORTH OF AN ELEMENT IN THIS POSITION

11.2-64-4131

FIGURE 17. CRITICAL CONFIGURATION IN THE GCRE CRITICAL ASSEMBLY, EXPERIMENTAL CORE

- ELEMENTS THAT MADE UP CRITICAL CONFIGURATION
- NOT IN CRITICAL CONFIGURATION
- WORTH OF AN ELEMENT IN THIS POSITION

FIGURE 18. CRITICAL CONFIGURATION IN THE GCRE CRITICAL ASSEMBLY, CLEAN CORE

Note: No burnable poison in positions 38, 61, 60 and 59; Core position numbers refer to "standard" GCRE critical assembly core

11.2-64-4133

FIGURE 19. CORE LAYOUT OF THE GCRE CRITICAL ASSEMBLY, Pb-1 CORE

d. Pb-2 Core

The Pb-2 core was a clean core with a lead reflector around a hexagonal array of 61 elements. The distance between the reflector and individual fuel elements varied from 1/8 to 3/4 in.; all elements contained burnable poison. The core went critical with 55 elements in the configuration shown in Figure 20.

e. Pb-3 Core

The Pb-3 core was identical to the Pb-2 core except that the lead reflector was separated from the outer row of elements by 12 inches. The core went critical with 56 elements in the configuration shown in Figure 21. Reduction of experimental data showed that this core could have gone critical with 55 elements.

f. Flooded Core

The Pb-3 core was flooded with mineral oil (mineral oil was used instead of water to minimize corrosion of the uranium foil) with an approximate molecular formulation of $C_{20}H_{42}$ and a density of 0.83 gm/cc. The resulting hydrogen density was about 10% greater than that of water. The critical configuration of 37 elements is shown in Figure 22.

g. Pb-3 Core with Higher Fuel Loading

This core was loaded with 33% more fuel than the basic Pb-3 core (404 g instead of 303 g of U^{235} per element) by increasing the fuel loading of each individual pin by that percentage. The core went critical with 47 elements in the configuration shown in Figure 23.

h. Pb-3 Core with Higher Steel Content

A basic Pb-3 core was modified by increasing the thickness of the four fuel cylinders from 0.040 to 0.50 in. After this increase in steel content, the core went critical with 58 elements in the configuration shown in Figure 24.

i. Uniform Power Distribution Core (UPDC)

The UPDC was identical to the Pb-3 core except that the fuel elements were not uniformly spaced. This core went critical with 57 elements in the configuration shown in Figure 25.

2. GCRE-I Reactor

Six critical experiments were performed in the GCRE-I reactor.

a. GCRE-I Core with Aluminum Tube Bundle (Dry)

This core used plate-type (IZ) fuel elements in an aluminum tube bundle. The experiment was performed with the gas passages

VALUES ARE % $\Delta K/K$

- ELEMENTS THAT MADE UP CRITICAL CONFIGURATION
- NOT IN CRITICAL CONFIGURATION
- WORTH OF AN ELEMENT IN THIS POSITION

FIGURE 20. CRITICAL CONFIGURATION IN THE GCRE CRITICAL ASSEMBLY Pb-2 CORE

11.2-64-4134

VALUES ARE % $\Delta k/k$

FIGURE 21. CRITICAL CONFIGURATION IN THE GCRE CRITICAL ASSEMBLY, Pb-3 CORE

VALUES ARE % $\Delta K/K$

- ELEMENTS THAT MADE UP CRITICAL CONFIGURATION
- NOT IN CRITICAL CONFIGURATION
- WORTH OF AN ELEMENT IN THIS POSITION

FIGURE 22. CRITICAL CONFIGURATION IN THE FLOODED GCRE CRITICAL ASSEMBLY

11.2-64-4136

VALUES ARE % $\Delta K/K$

FIGURE 23. CRITICAL CONFIGURATION IN THE GCRE CRITICAL ASSEMBLY WITH HIGHER FUEL LOADING

11-2-64-4137

VALUES ARE % $\Delta K/K$

FIGURE 24. CRITICAL CONFIGURATION IN THE GCRE CRITICAL ASSEMBLY WITH HIGHER STEEL CONTENT

11-2-CA-4138

ELEMENTS THAT MADE UP CRITICAL CON FIGURATION

NOT IN CRITICAL CONFIGURATION

FIGURE 25. CRITICAL CONFIGURATION OF THE UNIFORM POWER DISTRIBUTION CORE

11.2-64-4139

in the core dry. The core went critical with 59 fuel elements in the configuration as shown in Figure 26 (Ref. 1 and 2).

b. GCRE-I Core with Aluminum Tube Bundle (Flooded)

The GCRE-I core, with plate-type (IZ) elements in an aluminum tube bundle and the gas passages flooded with demineralized water, went critical with 36 elements. The critical configuration is shown in Figure 27. The 37 vacant core positions were filled with water, which had the effect of surrounding the 36 elements with a water reflector (Ref. 3 and 4).

c. GCRE-I Core with Stainless Steel Tube Bundle (Dry)

The GCRE-I core, with plate-type (IZ) elements in a stainless steel tube bundle and the gas passages dry, went critical with 65 elements. The critical configuration is shown in Figure 28 (Ref. 5 and 6).

d. GCRE-I Core with Stainless Steel Tube Bundle (Flooded)

The GCRE-I core with plate-type elements in a stainless steel tube bundle and the gas passages flooded with demineralized water, went critical with 52 elements in the configuration shown in Figure 29 (Ref. 5 and 7).

e. GCRE-I Core with Pin-Type Fuel Elements (Dry)

The GCRE-I core with pin-type (IB-2L) fuel elements in a stainless steel tube bundle with the gas passages dry, went critical with 54 elements in the configuration shown in Figure 30 (Ref. 8 and 9).

f. GCRE-I Core with Pin-Type Fuel Elements (Flooded)

The GCRE-I core with pin-type (IB-2L) fuel elements in a stainless steel tube bundle and with the gas passages flooded with demineralized water, went critical with 45 elements in the configuration shown in Figure 31 (Ref. 10 and 11).

3. ML-1-IA Critical Assembly

The ML-1-IA critical assembly was used to perform one critical experiment. The core went critical with 59 tube-type fuel elements in the configuration shown in Figure 32 (Ref. c).

4. ML-1-IB Critical Assembly

Three critical experiments were performed with the ML-1-IB critical assembly. This assembly used a composite pin-type core in which some fuel pins were filled with standard fuel pellets and some with compacted-powder fuel.

FIGURE 26. CRITICAL CONFIGURATION GCRE-I; ALUMINUM TUBE BUNDLE; 12 ELEMENTS, DRY

11-2-64-4140

FIGURE 27. CRITICAL CONFIGURATION GCRE-I; ALUMINUM TUBE BUNDLE; 12 ELEMENTS, FLOODED

11.2-64-4141

FIGURE 30. CRITICAL CONFIGURATION GCRE-I; STAINLESS STEEL TUBE BUNDLE; IB-2L ELEMENTS, DRY

FIGURE 31. CRITICAL CONFIGURATION GCRE-1; STAINLESS STEEL TUBE BUNDLE; IB-2L ELEMENTS, FLOODED

112-64-4145

ELEMENTS THAT MADE UP CRITICAL CONFIGURATION

NOT IN CRITICAL CONFIGURATION

11Z-64-4146

FIGURE 32. CRITICAL CONFIGURATION ML-1-IA CRITICAL ASSEMBLY

a. ML-1-IB Critical Assembly without Shims

The core went critical with no reactivity shims and with the gas passages dry with 48 fuel elements in the configuration shown in Figure 33.

b. ML-1-IB Critical Assembly with Stainless Steel Shims (Dry)

The core went critical with stainless steel shims installed on all fuel elements and with the gas passages dry with 51 elements in the configuration shown in Figure 34.

c. ML-1-IB Critical Assembly with Stainless Steel Shims (Flooded)

The core went critical with stainless steel shims installed on all fuel elements and with the gas passages flooded with demineralized water with 43 elements in the configuration shown in Figure 35.

5. ML-1 Reactor

Six critical experiments were performed in the ML-1 reactor.

a. ML-1 Reactor Without Shims (Dry)

The dry ML-1 core without shims went critical with 48 elements in the configuration shown in Figure 36 (Ref. 12 and 13).

b. ML-1 Reactor with Stainless Steel Shims

The dry core with stainless steel shims went critical with 49 elements in the configuration shown in Figure 37. Only those core positions that were loaded with fuel elements were shimmed (Ref. 12).

c. ML-1 Reactor with Silver Shims

With light silver shims, the dry core went critical with 55 fuel elements in the configuration shown in Figure 38.

d. ML-1 Reactor without Shims (Flooded)

The ML-1 core, with no reactivity shims and with the gas passages flooded with demineralized water, went critical with 35 fuel elements in the configuration shown in Figure 39 (Ref. 14 and 15).

e. ML-1 Reactor with Stainless Steel Shims (Flooded)

The ML-1 core, with stainless steel reactivity shims and with the gas passages flooded with demineralized water, went critical with 37 elements in the configuration shown in Figure 40 (Ref. 14).

FIGURE 33. CRITICAL CONFIGURATION ML-1-IB CRITICAL ASSEMBLY, DRY, WITHOUT SHIMS

11-2-64-4147

FIGURE 34. CRITICAL CONFIGURATION ML-1-IB CRITICAL ASSEMBLY, DRY, WITH SHIMS

11.2-64-4148

FIGURE 35. CRITICAL CONFIGURATION ML-1-IB CRITICAL ASSEMBLY, FLOODED, WITH SHIMS

11-2-64-4149

FIGURE 36. CRITICAL CONFIGURATION ML-1, DRY, WITHOUT SHIMS

FIGURE 37. CRITICAL CONFIGURATION ML-1, DRY, WITH STAINLESS STEEL SHIMS

FIGURE 38. CRITICAL CONFIGURATION ML-1, DRY, LIGHT SILVER SHIMS

Total silver-plating: 0.00175 inches of silver: heavy silver shims used 0.005 inches of silver.

11.2-64 4152

FIGURE 39. CRITICAL CONFIGURATION ML-1, FLOODED, WITHOUT SHIMS

FIGURE 40. CRITICAL CONFIGURATION ML-1, FLOODED, STAINLESS STEEL SHIMS

11-2-64-4154

f. ML-1 Reactor with Light Silver Shims

The ML-1 core, with light silver shims and the gas passages flooded with demineralized water, went critical with 48 elements in the configuration shown in Figure 41.

B. INTERPRETATION OF CRITICALITY DATA

The results of the critical experiments are summarized in Table 2. Comparison of the data obtained with the various systems reveals certain characteristics of these systems. Because the cores were not identical and because the worth measurements were not made in every core position in each system, several methods of evaluating the reactivity worths of the various cores had to be used with the consequence that considerable scatter appeared in the numerical results.

1. Worth of Burnable Poison

Data from experiments with the GCRE critical assembly indicate that burnable poison in all elements would increase the critical loading from 54 to 64 elements. The increase in reactivity associated with the increase in loading can be approximated by assuming that each additional element was worth $0.22\% \Delta K/K$. Thus, a net increase of $2.2\% \Delta K/K$ compensated for the poison in 54 elements or the average value for poison in a single element was $-0.04\% \Delta K/K$.

2. Worth of Lead Reflector

Based on the assumptions stated above and considering the fact that the Pb-3 core went critical with 56 elements, the Pb-3 reflector is calculated to be worth about $3.4\% \Delta K/K$ more than a water reflector.

3. Effect of Lead Reflector Spacing

Comparison of the data from the Pb-2 and the Pb-3 cores (which went critical with 55 and 56 elements, respectively) leads to the conclusion that small variations in lead spacing do effect core reactivity. The Pb-3 core was worth approximately $0.18\% \Delta K/K$ less than the Pb-2 core.

4. Worth of Fuel Addition

Comparison of the data from the Pb-3 core (critical with 55 elements) with data from the same core loaded with one-third more fuel (critical with 47 elements) shows that the additional fuel is worth approximately $+4.4\% \Delta K/K$. This is equivalent to about $+0.76\% \Delta K/K$ per kg of U^{235} added to the critical core.

5. Worth of Stainless Steel Addition

The Pb-3 core data compared with data from the same core with thicker fuel tubes showed that two more elements were required to compensate for the greater amount of stainless steel. This indicates that the AISI Type 316 stainless steel addition was worth $-1.15\% \Delta K/K$, or $-0.053\% \Delta K/K$ per

Light silver shims were plated with 0.00175 inches of silver

kg of stainless steel.

6. Effect of Change in Fuel Element Spacing

The critical number of elements in the Pb-3 core (56) compared with the critical number of elements in the uniform radial power core (57), leads to the conclusion that the change in element spacing is worth approximately $-0.75\% \Delta K/K$.

7. Effect of Flooding

A comparison of the critical configuration of the Pb-3 core with 56 elements and the critical configuration of the same core flooded with mineral oil, indicates that the flooding has the same worth as 19 elements or approximately $+7.6\% \Delta K/K$.

The flooded GCRE-I reactor with aluminum tube bundle and plate-type elements went critical with 36 elements or 23 elements less than the same core in the dry condition. If it is assumed that the peripheral elements in the GCRE-I core were worth about the same as in the Pb-3 core, the flooding water is worth about $+9.2\% \Delta K/K$.

The GCRE-I reactor core with stainless steel tube bundle and plate-type elements required 52 elements to go critical when flooded, compared to 66 elements for the same core in a dry condition. This difference of 14 elements indicates that flooding this core was worth approximately $+5.1\% \Delta K/K$.

The GCRE-I core with stainless steel tube sheets and pin-type elements went critical with 45 elements when flooded and 54 elements when dry. The flooding was equivalent to 9 elements, or approximately $+4.5\% \Delta K/K$.

When the ML-1-IB core was flooded, the core went critical with 42 elements, 9 elements less than in a dry condition. The flooding was worth approximately $+4.5\% \Delta K/K$.

The ML-1 core went critical with 35 elements when flooded and with 48 elements when dry. Table 2 shows that the peripheral elements in the second ring of elements (second inward from the reflector) are worth $0.60\% \Delta K/K$ (Figure 39). If it is assumed that the worth of the elements in the outer ring is the same as the similarly positioned elements in the ML-1-IB critical assembly, namely $0.5\% \Delta K/K$, the effect of flooding the dry ML-1 core with water is worth approximately $+6.5\% \Delta K/K$.

The ML-1 core with stainless steel shims required 12 less elements to achieve flooded criticality than were required for the dry core. On the basis of a peripheral element worth of $0.5\% \Delta K/K$ in the flooded core and $+0.45\% \Delta K/K$ for the peripheral element worth in the dry core, the flooding of the shimmed ML-1 core is worth about $+5.4\% \Delta K/K$.

The ML-1 core with light silver shims required 7 more elements to go critical in the dry condition than in the flooded condition. This establishes the flooding to be worth approximately $+3.5\% \Delta K/K$.

A summary of the reactivity changes associated with flooding is given in Table 3.

TABLE 3 - ESTIMATED WORTH OF FLOODING GAS PASSAGES

<u>Reactor or Critical Assembly</u>	<u>Core</u>	<u>No. of Elements for Criticality</u>		<u>Worth of Flooding*, %Δ K/K</u>
		<u>Dry</u>	<u>Flooded</u>	
GCRE critical assembly	Pb-3	56	37	+7.6
GCRE-I reactor (aluminum tube bundle)	IZ	59	36	+9.2
GCRE-I reactor (stainless steel tube bundle)	IZ	66	52	+5.1
	IB-2L	54	45	+4.1
ML-1-IB critical assembly	Steel shims	51	42	+4.5
ML-1 reactor	No shim	48	35	+6.5
	Steel shims	49	37	+5.4
	Light silver shims	55	48	+3.5

*Approximate values.

C. REACTOR OPERATING CORES

The GCRE-I reactor operating core installed in October 1960 had an estimated excess reactivity of $1.0\% \Delta K/K$. Figure 42 shows the configuration of the core and the worth of some individual elements (Ref. 16 and 17).

The ML-1 reactor operating core installed in April 1961 contained 61 elements with 28 heavy silver shims and had an excess reactivity of about $1.5\% \Delta K/K$ (Ref. 18). The measured values of peripheral element worth are shown in Figure 43.

D. MODERATOR TEMPERATURE COEFFICIENTS

The reactivity changes resulting from variations in moderator temperature were measured in five different systems:

- GCRE critical assembly with the clean core and water reflector (Ref. a)
- GCRE critical assembly with the lead reflector (Ref. a)
- The GCRE-I reactor with stainless steel tube bundle (Ref. 19)
- The ML-1-IB critical assembly (Ref. d)
- The ML-1 reactor (Ref. 20).

The values of these temperature coefficient are presented graphically in

FIGURE 42. GCRE-I OPERATING CORE CONFIGURATION

FIGURE 43. ML-1 OPERATING CORE

Figure 44. The curves for the ML-1-IB critical assembly and the ML-1 reactor (curves 1 and 5) are in good agreement. These cores have identical geometry but the ML-1-IB critical assembly element had 648 gm of U^{235} per element and the ML-1 element had 810 gm U^{235} per element.

A direct comparison between temperature coefficients for the GCRE critical assembly (lead reflector) and the GCRE-I may not be valid since the critical assembly used tube-type elements in an aluminum tube bundle and the GCRE-I used pin-type elements in a stainless steel tube bundle.

E. VOID COEFFICIENT

Two types of void coefficients were measured in the GCRE critical assembly. The first estimated the worth of a large void near the core periphery in the "experimental core" (Ref. a). This was done by placing an empty pressure tube in core positions 57 and 44 (see Figure 17). The total void was worth $-0.14\% \Delta K/K$. Considering the void to be effective over the fuel length of 28 in. (71.12 cm), the total void volume is 171.6 in.³ (2821.90 cc) and the void coefficient is $-0.5 \times 10^{-6} \Delta K/K\text{-cc}$.

The second measurement was made in the ML-1-IB core with tube-type elements (Ref. c) by placing polyethylene at the moderator-reflector interface of the core. Polyethylene, which has a higher hydrogen density than water, acted as a negative void. Considering the void to be effective over the active fuel length of 28 in., the worth of a void 0.06 cm thick was found to be $1.1 \times 10^{-4} \Delta K/K$. The void coefficient associated with the 0.06 cm void is $-0.1 \times 10^{-6} \Delta K/K\text{-cc}$, which is in fair agreement with the first value.

F. CONTROL BLADE STUDIES

Two types of control blades were used in the reactor systems. The GCRE-I used 12, individual, horizontally-acting, blades and the ML-1 is equipped with six pairs of semaphore-type blades.

1. Worth Measurement in Dry GCRE Critical Assembly

The largest amount of experimentation relative to the worth of control blades was performed in the GCRE critical assembly (Ref. a). Measurements of blade worth were made in four different critical configurations: the experimental core, the clean core, the core with a lead reflector and the core flooded with mineral oil. The characteristics of fourteen different control blades mockups used in the experiment are listed in Table 4.

Composite blades containing indium were made by placing a sheet of indium on one side of the base (tungsten or aluminum) blade. The cadmium composite blade was made by covering all surfaces of the base (tungsten or aluminum) blade with cadmium foil. The method used to make composite blades resulted in different cross sectional areas (see Table 4) and, consequently, in different amounts of water displaced. This factor must be taken into consideration when comparing indicated blade worths.

Worth measurements were made in the dry core at two different axial locations in three radial positions. The insertion distance was

FIGURE 44. MODERATOR TEMPERATURE COEFFICIENTS

TABLE 4 - DIMENSIONS OF MOCKUP CONTROL BLADES USED IN THE GCRE CRITICAL ASSEMBLY

No.	Blade Type	Blade Dimensions, Thickness by Width, in inches					Cross-Sectional Area, in. ²	Water Displacement Ratio
		Tungsten	Indium	Cadmium*	Aluminum	Polyethylene		
1	Tungsten	0.2 x 2	-	-	-	-	0.4	1.0**
2	Tungsten	0.2 x 3	-	-	-	-	0.6	1.5
3	Tungsten-Indium Cadmium	0.2 x 7	0.062 x 7	0.010	-	-	1.98	5.0
4	Tungsten-Indium Cadmium	0.2 x 8	0.062 x 8	0.010	-	-	2.26	5.7
5	Tungsten-Cadmium	0.2 x 2	-	0.010	-	-	0.44	1.1
6	Tungsten-Indium	0.2 x 2	0.062 x 2	-	-	-	0.52	1.3
7	Tungsten-Indium Cadmium	0.2 x 4	0.062 x 4	0.010	-	-	1.13	2.8
8	Tungsten-Indium Cadmium	0.2 x 2	0.062 x 2	0.010	-	-	0.57	1.4
9	Tungsten-Indium Cadmium	0.2 x 14	0.062 x 14	0.010	-	-	3.95	9.9
10	Tungsten-Indium Cadmium	0.2 x 24	0.062 x 24	0.010	-	-	6.77	17.0
11	Aluminum-Indium Cadmium	-	0.062 x 2	0.010	0.2 x 2	-	0.57	1.4
12	Aluminum-Indium Cadmium	-	0.062 x 10	0.010	0.2 x 10	-	2.83	7.1
13	Aluminum-Cadmium	-	-	0.010	0.2 x 2	-	0.44	1.1
14	Polyethylene-Cadmium	-	-	0.010	-	0.2 x 2	0.44	1.1

* Cadmium was wrapped on all surfaces of materials used in combination with it

**Reference blade

measured from the periphery of the nominal core which had a radius of 12 in. (see Figure 45). The blade worths measured in the dry core are given in Table 5.

2. Worth Measurements in the Simulated Flooded Core

Control blade worth measurements were performed in the simulated flooded core with the control blade configuration as originally proposed for the GCRE-I. Table 6 gives the results of these measurements.

The original shutdown-rod configuration for the GCRE had eight blades in positions A1, A2, B1, B2, C1, C2, D1 and D2 (see Figure 45). The large negative reactivity resulting from this configuration required that a combination of measurements be made to determine the worth of the blades. Using the data on lines 2, 3 and 5 of Table 6, and assuming that all blade pairs are approximately similar and that a peripheral element is worth about $0.4\% \Delta K/K$, it can be concluded that the shutdown blades can control 71 elements. However, this evaluation neglects shadowing effects; if such effects exist, the blades will not control a 71-element core (the shadowing effect is described in paragraph III-F-5).

A single measurement using four large blades was made to confirm the original test. Three of the blades were made from cadmium, indium and tungsten (referring to Table 4; two were type 9; one was type 10) and one (type 12) was made of aluminum, indium and cadmium. This combination of blades resulted in a subcritical assembly which extrapolated to critical at 66.5 elements.

3. Worth of the GCRE-I Reactor Control Blades

When the GCRE-I was built, the worth of the blades was measured (Ref. 19). The reactivity worth as a function of blade position is presented in Figure 46, along with the worth of the shim gang (Shim 1 and 2 ganged). A direct comparison between these values and those measured in the GCRE critical assembly is not possible because the dimensions of the blades used in the reactor were different from those of the blades evaluated in the critical assembly.

4. Worth Measurements in the ML-1-IA Critical Assembly

Worth measurements of control blade configurations possible for use in the ML-1 were made in the ML-1-IA critical assemblies (Ref. c). The first measurements of blade worths for various blade positions were made with a stainless steel blade pair (Figure 47) in the 61-element ML-1-IA core. Subsequently, these blades were wrapped with 0.020 in. of cadmium and a second set of measurements were made (Figure 48).

5. Worth Measurements in the ML-1-IB Critical Assembly

Measurements were made in the ML-1-IB critical assembly with blades made of the reference ML-1 control blade materials (Ref. d) (silver-indium-cadmium alloy for the shim blades and stainless steel for the regulating blades). Blade construction is shown in Figure 49 and the experimental

α 15 inches INSERTED POSITION
 β 13.5 inches PAST INSERTED POSITION
 γ 11 inches INSERTED POSITION
 δ 5.5 inches INSERTED POSITION

FIGURE 45. LOCATION OF CONTROL BLADES IN GCRE CRITICAL ASSEMBLY

11.2.64-4159

TABLE 5 - WORTH OF EXPERIMENTAL BLADES IN DRY GCRE CRITICAL ASSEMBLY CORE

Blade Type No.*	Blade Type	Pos.**	Worth, % Δ K/K			
			Experimental Core @ 15 in. Inserted Pos.**	Clean Core		Lead Reflector Core @ 11 in. Inserted**
				@ 11 in.**	@ 5.5 in.**	
1	Tungsten (2 in. wide)	B-1	-0.399	-	-	-
		B-2	-0.700	-	-	-
5	Tungsten-Cadmium	B-1	-0.549	-	-	-
		B-2	-0.934	-	-	-0.498
2	Tungsten (3 in. wide)	B-1	-0.439	-	-	-
8	Tungsten-Indium Cadmium	B-2	-	-0.452	-0.126	-0.546
65 7	Tungsten-Indium Cadmium	B-2	-	-	-0.193	-
13	Aluminum-Cadmium	B-2	-	-	-	-0.432
12	Aluminum-Indium Cadmium	B-2	-	-	-	-0.476
14	Polyethylene-Cadmium	B-2	-	-	-	-0.477

* See Table 4

**See Figure 45

TABLE 6 - WORTH OF EXPERIMENTAL BLADES IN SIMULATED
FLOODED GCRE CRITICAL ASSEMBLY CORE

Blades inserted 1.5 in. past core centerline

<u>Blade Width and Position*</u>	<u>No. of Fuel Elements</u>	<u>Excess Reactivity Left in Core, % $\Delta K/K$</u>
None	37	0.0
8 in. blades (4) at A-2 & D-2	46	0.16
8 in. blades (4) at A-1, A-2, C-1, C-2	49	0.17
8 in. blades (4) at A-1, A-2, B-1, B-2	49	0.25
8 in. blades (4) at A-1, A-2, B-7	49	0.51
7 in. blade (3) at B-2		
8 in. blades (4) at A-1, A-2, D-1, D-2	49	0.44
8 in. blades (4) at A-2, B-2, C-2, D-2	54	0.18
24 in. blades (10) at B & C		
14 in. blade (9) at E, and	66.5***	-
10 in. blade (11) at A		

* Numbers in parentheses refer to blade designation in Table 4; A-Z, D-Z, etc., refer to bottom right sketch in Figure 45.

***Extrapolation from subcritical data.

FIGURE 46. WORTH OF GCRE-I BLADES IN DRY CORE

11.2-6-4-4160

FIGURE 47. ML-1-IA MOCKUP CONTROL BLADE

FIGURE 48. WORTH OF SIMULATED ML-1 BLADE IN THE ML-1-IA CRITICAL ASSEMBLY

blade worths are shown in Figure 50.

One of the problems with control blades is the so-called "shadowing" effect. When adjacent control blades are inserted into the core simultaneously, the blades interfere neutronically and thus reduce the worth of each blade. This effect was measured in the ML-1-IB critical assembly (Figure 51). Two sets of blades were available, one set used the reference materials (silver-indium-cadmium) and the other set the "BMI blade" (stainless steel wrapped with cadmium). The lower curve indicates the change in total worth of the BMI blades as additional BMI blades are added. It is anticipated that the addition of a fourth blade would have little or no effect on the worth of the base blade. The upper curve indicates the worth of a single reference blade and the worth of that blade in the presence of a BMI blade. It should be noted that this effect is probably not as large as could be experienced if another reference blade were used. The shadowing which occurs with two BMI blades is about 11% and the shadowing with a reference blade and one BMI blade is about 6.4%. However, the reference blades because of their large size, displaced about 8.6% more moderator water than the BMI blade. To be conservative, it was assumed that the shadowing effect in the reference case will be the same as in the BMI blade; about 11% for two blades and about 13% for three (Figure 51).

6. Worth Measurements in the Flooded ML-1-IB Critical Assembly

In the ML-1 reactor, the core must be flooded with water for refueling. At this time, the six semaphore blades are fully inserted to maintain the core in a subcritical condition. The worth of the six blades in the flooded ML-1 core was simulated in the flooded ML-1-IB critical assembly by using four sets of BMI blades, one set of ML-1 reference blades and a set of stainless steel blades (Ref. d). The 61-element core with these blades went critical with a measured excess of 0.284% at 23°C moderator temperature at the maximum blade worth position (15° separation).

7. Worth of the ML-1 Control Blades in the Dry Core

The ML-1 control blade system consists of five pairs of shim-scam blades made of 80% Ag-15% In-5% Cd and a pair of regulating blades made of stainless steel (Ref. 21, 22 and 23). The construction of these blades is quite similar to that of the ML-1-IB mockup blades. ML-1 blade pair worth as a function of position is shown for a shim-scam blade and the regulating blade in Figure 52. Only one shim-scam blade pair (Shim 2) was calibrated; the symmetrical location of the shim rods makes possible the assumption of identical worths for all such rods.

8. Worth of ML-1 Control Blades in the Flooded Core

Worth curves (Figure 53) for single ML-1 control blade pairs in the unshimmed core and in the light-silver-shimmed cores were plotted from flooded core data. The curve shown for the ML-1 core without shims has a different shape than the curve in the shimmed core; this can be attributed to the fact that a 35-element core has no fuel elements in the outer ring. The shape of the curve for the light-silver-shim core compares quite

FIGURE 49. ML-1-IB MOCKUP CONTROL BLADE

FIGURE 50. WORTH OF MOCKUP CONTROL BLADE IN THE ML-1-IB CRITICAL

FIGURE 51. SHADOWING EFFECT WITH CONTROL BLADES

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FIGURE 52. ML-1 CONTROL BLADE AND CONTROL BLADE WORTH

well with the shapes of the curves for the standard dry core with 28 heavy silver shims.

9. Worth of Semaphore-Type Blades

A graphical comparison of the blade worths measured in the three different cores is shown in Figure 54. The ML-1-IB blades have a maximum worth of about 1.8% $\Delta K/K$ while the ML-1-IA blades are worth about 1.1% $\Delta K/K$. The difference is due to the difference in blade size and material and the difference in the length of the cores. The ML-1-IA blades were 14-in. long, the ML-1-IB blades approximately about 11-in. long. Since both cores were normally 22 in. in diameter; the ML-1-IA blade, in the fully inserted position, extended over a much larger section of the core. Since both blades are black to thermal neutrons, the difference in worth due to differences in material is small compared to the other two effects.

The ML-1-IB control blades were approximately the same size as the ML-1 control blades, but there was a significant difference in worth (Figure 54). This is due to the heavy silver shims in the ML-1 core, which significantly flatten the power and flux, and thus, change the blade worth.

G. POWER AND FLUX DISTRIBUTION

Two types of flux and power distributions must be considered when studying the heterogeneous ML-1 type reactor: the overall reactor axial and radial distributions and the single element (or intracell) distributions. These distributions were established for the various systems and are reported below.

1. Core Radial Power Distribution

A uniform radial power distribution is desirable to maximize the thermal power while minimizing the cladding hot spot temperature. In the initial GCRE-I core design (with uniform element spacing), an attempt was made to achieve the uniform hot spot temperatures by orificing of the gas coolant flow. For the ML-1, it was decided to use a non-uniform lattice spacing to achieve uniform radial power generation.

Radial power distributions were determined in six cores:

- GCRE Critical Assembly, Experimental Core (Ref. a)
- GCRE Critical Assembly, Pb-3 Core (Ref. a)
- GCRE Critical Assembly, Uniform Radial Power Distribution Core (Ref. b)
- GCRE-I Reactor (Ref. 24).
- ML-1-IB Critical Assembly (Ref. d)
- ML-1 Reactor (Ref. 25).

FIGURE 53. WORTH OF ML-1 CONTROL BLADES IN FLOODED CORES

FIGURE 54. COMPARISON OF WORTHS OF SEMAPHORE BLADES

Various techniques were used in making these measurements. Measurements made in the GCRE critical assembly used the catcher-foil technique; aluminum foils were placed adjacent to the fuel to catch recoiling fission products. Power in the GCRE-I reactor was determined from outlet coolant temperature and flow data. Temperature probes were used to determine the mixed mean temperature of the gas leaving each element. Fuel capsules from the center fuel pin were used to determine radial power distribution in the ML-1-IB critical assembly. Power in the ML-1 reactor was determined with fuel capsules and flux wires and the data were used to calculate the integrated power in each element.

Radial power distributions for each of the systems are plotted in Figure 55. Curves 1 and 2 show the radial power distribution for the GCRE critical assembly experimental core and the GCRE critical assembly Pb-3 core, respectively. The basic difference between the two systems is the addition of burnable poison to all elements of the lead-reflected core and the replacement of the water reflector with a lead reflector. Since the burnable poison should have only a small effect on the radial power distribution, the difference in distribution can be attributed almost entirely to the lead reflector. Curve 3 shows the radial power distribution in the GCRE critical assembly uniform radial power distribution core. Curve 4 shows the GCRE-I core radial power distribution. It is apparent that the spacing resulted in more radial power variation than was desired. These data were used to determine the spacing requirements for the ML-1-IB critical assembly; the radial power distribution in this assembly is shown in curve 5 of Figure 55.

The element spacing used in the ML-1 core was the same as that of the ML-1-IB critical assembly except during the mapping experiments, when 28 shims were incorporated in the ML-1 core (see Section IV-H-3). These shims, although primarily designed to control reactivity, significantly affected the power distribution. The radial power distribution for the ML-1 is shown in curve 6 of Figure 55. The power closely approached the desired flat distribution.

2. Core Radial Flux Distribution

The radial flux distribution was determined in the critical assemblies; the radial flux distribution could not be determined in either the GCRE-I or the ML-1 reactor because of the difficulty of placing flux measuring wires in the moderator and the fuel elements.

In the critical assembly, the flux was measured by p-metal (manganese alloy) wire activation in the moderator region and in the center of the fuel element. Moderator flux measurements were made in the GCRE critical assembly with both a clean core and an experimental core. The normalized radial flux distribution for these cores is presented in Figure 56.

The radial flux distribution at the center of the fuel elements was determined in four cores:

- GCRE critical assembly, clean core (Ref. a)
- GCRE critical assembly, experimental core (Ref. a)

FIGURE 55. RADIAL POWER DISTRIBUTION

- ML-1-IA critical assembly (Ref. c)
- ML-1-IB critical assembly (Ref. d)

Normalized radial flux distribution in these cores is presented in Figure 57.

3. Axial Flux Distribution

The axial flux distribution was determined in the critical assemblies and in the ML-1 reactor. In the GCRE (Ref. a) and ML-1-IA (Ref. c) critical assemblies, the axial flux was measured by placing a full length p-metal wire in the moderator water midway between two fuel elements. In the ML-1-IB critical assembly, the wire was placed on the outer surface of the fuel element insulation liner. In the ML-1 reactor, a full length gold wire was placed between the inner and outer fuel element liners (Ref. 25).

Axial flux distributions in the 28-in. tube-type elements are presented in Figure 58. The most important feature in this figure is the significant shift in axial flux distribution due to the burnable poison. (The experimental core was the only one without burnable poison.)

The measured axial flux dip in the 22-in. pin-type cores in the burnable poison area is relatively small compared to that in the tube-type elements (Figure 59). This is due in part to the quantity of burnable poison used; both the tube- and pin-type elements used cadmium burnable poison, but the tube-type elements had approximately 5.4 times more cadmium. The great difference in axial flux distribution between the ML-1 and the critical assembly is due to the heavy silver shims; Figure 59 shows that the shims shift the peak axial flux toward the top of the fuel.

4. Axial Power Distribution

In general, the element axial power distribution will follow the same distribution as the flux. The power at a given axial position is defined here as the sum of the power produced at that position in all fuel annuli or in all fuel pins which make up a fuel element. Each fuel annulus or fuel pin within an element, however, will exhibit an axial power distribution slightly different from that of other annuli or pins in the same element. The degree of difference depends, to a large extent, on the radial gradients across a fuel element. The pins or annuli in element in the center of the core exhibit only small differences; the differences in peripheral elements are significant.

Typical axial power distributions within a concentric tube-type fuel element are shown in Figure 60 (Ref. a). The figure shows axial power distribution in each of the four fuel annuli which made up the element, and the dependence of power distribution on radial position. The data presented are for the clean core with a burnable poison strip 5 in. wide, centered at 15 in. from the bottom of the fuel.

The situation depicted in Figure 60 also exists in the pin-type fuel elements; i.e., each of the pins in an element exhibits a different axial power distribution. This effect was measured in both the ML-1-IB

FIGURE 56. RADIAL FLUX DISTRIBUTION IN THE MODERATOR OF THE GCRE-CRITICAL ASSEMBLY

FIGURE 57. RADIAL FLUX DISTRIBUTION IN THE CENTER OF FUEL ELEMENTS OF THE CRITICAL ASSEMBLIES

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FIGURE 58. AXIAL FLUX DISTRIBUTION IN TUBE-TYPE ELEMENTS

FIGURE 59. AXIAL FLUX DISTRIBUTION IN PIN-TYPE ELEMENTS

critical assembly (Ref. d) and the ML-1 reactor (Ref. 25 and 26). Figure 61 shows the experimentally measured power distribution for the center position in the ML-1 core. Note that the axial flux decreases more rapidly than in the core with a tube-type element, due to the heavy silver shims on the lower 12 in. of the fuel in the ML-1. These shims also dampen significantly the axial variations due to burnable poison.

5. Flux Distribution Within the Moderator Surrounding Individual Elements

When the relative positions of the individual elements in the ML-1 core are considered, it is obvious that radial flux gradients exist across all fuel elements in the core except the element in the center position. In addition, since the fuel is in the center region of a cell, and all the moderator is located outside the fuel region, the flux will increase in the moderator water. The magnitude of these effects was measured in the ML-1-IB critical assembly by mapping the moderator flux (Ref. d) in three core positions: fuel element position 1 (the core center; fuel element position 29; and fuel element position 49 (adjacent to the reflector). Only a 180° segment of the moderator was mapped in fuel element position 1. It was assumed that in this core position the flux level would be independent of direction (Figure 62). Fuel element position 28 was fully mapped (Figure 63). This fuel element position is located one ring of elements away from the edge of the core and it is anticipated that a flux gradient will exist across the element. A full 360° map was also made of fuel element position 49, adjacent to the lead reflector (Figure 64). The flux gradient in this position is quite apparent on the flux map, which shows that the flux on the reflector side is about 40% less than that on the reactor side.

6. Intracell Flux Distributions

Both the GCRE-I reactor and the ML-1 reactor are extremely heterogeneous systems: The fuel is contained in an element surrounded by moderator water and, within each element, the fuel is contained in individual pins surrounded by cladding and located in a void. Since it is difficult to calculate flux distributions in such systems, typical intracell flux distributions were measured.

Intracell flux measurements were made only in the GCRE and the ML-1-IB critical assemblies. Such measurements could not be performed in either the ML-1 or the GCRE-I reactors because access to the moderator space was not available.

The thermal flux distribution through the central fuel element in the GCRE critical assembly experimental core is shown in Figure 65 (Ref. a). This figure shows the flux drop across the fuel annuli and in the moderator. Two curves are shown for the latter; note that the flux curves end on two different radii. As the sketch in Figure 65 shows, the upper curve (A) represents the flux along a line between two adjacent elements and the lower curve (B) represents the flux along a line through the center of an adjacent element.

The intracell flux distribution was also measured in the

CENTRAL CORE POSITION

FIGURE 60. AXIAL POWER DISTRIBUTION IN TUBE-TYPE ELEMENTS

FIGURE 61. AXIAL POWER DISTRIBUTION IN PIN-TYPE ELEMENTS

FIGURE 62. MODERATOR FLUX MAP, FUEL ELEMENT CORE POSITION 1, ML-1-IB CRITICAL ASSEMBLY

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FIGURE 63. MODERATOR FLUX MAP, FUEL ELEMENT CORE POSITION 28
ML-1-IB CRITICAL ASSEMBLY

112-64-4171

FIGURE 64. MODERATOR FLUX MAP, FUEL ELEMENT POSITION 49, ML-1-IB CRITICAL ASSEMBLY

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experimental core both in the flooded and dry condition (Figure 66). Since intracell flux distribution is highly dependent on core position, measurements were made of the flux in the fuel region at three radial positions. These measurements are presented graphically in Figure 67 which shows both the total and epicalcium flux distributions.

Detailed measurements of flux were also made in the ML-1-IB critical assembly (Ref. d). The flux distribution in a pin-type element is more difficult to obtain than in an annular tube-type element because the element is not radially symmetrical.

The flux distribution in the ML-1-IB critical assembly elements was measured by placing p-metal wires in the center of fuel capsules, wrapping p-metal wires circumferentially on a fuel capsule, attaching p-metal wires to the inner liner, and placing p-metal wires in the moderator water. The circumferentially wrapped wire measured the flux around the capsule and permitted a determination of average surface flux. All other wires were placed vertically and therefore measured the flux at one radial point. The measured thermal flux for the standard pellet type critical assembly is shown in Figure 68.

7. Intracell Power Distribution

Intracell power distributions were obtained in GCRE critical assemblies (Ref. a and b), ML-1-IB critical assemblies (Ref. c and d), and in the ML-1 reactor (Ref. 25).

In the cores studied, the power produced in an element is highly dependent on radial location of the element in the core. The intracell power distribution in three core positions in the GCRE critical assembly experimental core is shown in Figure 69. All data are presented as a function of radial distance from the center of the fuel element. It should be noted that positions 14 and 50 see a core radial flux gradient and, as a consequence, do not display a symmetrical intracell power distribution.

Measurements of power distribution were also made in the ML-1-IB critical assembly. The intracell power distribution for the standard element is presented in Figure 70. In addition, the intracell power distribution was measured in the ML-1 reactor. These measurements showed that the power distribution was fairly flat in each of the central 37 elements.

8. Axial Power Perturbation in Fuel Pin Near Control Blades

The effects of control blades on the flux in the fuel pins were investigated in both the ML-1-IB critical assembly (Ref. d) and in the ML-1 reactor (Ref. 25 and 26). Since each pin in every element is affected differently, it is not feasible to present all the data in this summary. A typical axial power distribution near a control blade pair is shown in Figure 71. Core position 1-D, shown in this figure, is a peripheral core position (see Figure 36) and as such will experience the maximum perturbation. Pin 12, adjacent to the control blades, sees the largest perturbation.

FIGURE 65. INTRACELL FLUX DISTRIBUTION: DRY GCRE EXPERIMENTAL CORE, TUBE-TYPE ELEMENTS

FIGURE 66. INTRACELL FLUX DISTRIBUTION: GCRE EXPERIMENTAL CORE, TUBE-TYPE ELEMENTS

FIGURE 67. RADIAL POSITION INTRACELL FLUX DISTRIBUTION IN THE GCRE CRITICAL ASSEMBLY EXPERIMENTAL CORE

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FIGURE 68. INTRACELL FLUX DISTRIBUTION: DRY CORE, PIN-TYPE ELEMENTS

FIGURE 69. RADIAL POSITION INTRACELL POWER DISTRIBUTIONS IN THE GCRE CRITICAL ASSEMBLY EXPERIMENTAL CORE

FIGURE 70. INTRACELL POWER DISTRIBUTION: ML-I-IB PIN-TYPE ELEMENTS

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FIGURE 71. POWER DISTRIBUTION ADJACENT TO A CONTROL BLADE IN THE ML-1 REACTOR

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9. Operating GCRE-I Core Power Map

Power production in each element in the GCRE-I (Ref. 24) was derived from coolant gas temperature data and is shown in Figure 72.

10. Operating ML-1 Core Power Map

The power produced in each element in the ML-1 reactor was obtained by irradiating fuel capsules in representative core positions (Ref. 25). Measurements were made with shim-scam control blade pairs at three positions (46°, 65° and 80° withdrawn) with all other blades fully withdrawn (Figure 73).

11. Cadmium Ratios in the ML-1

Cadmium ratios were also obtained in the dry (Ref. 25) and flooded (Ref. 27) ML-1 reactor. The cadmium ratio is defined here as the ratio of the total power to epi-cadmium power when power is defined as the gamma activity of the specimen after irradiation. Values are averaged over the entire pin. Epi-cadmium power was obtained by counting the activity of a specimen which was covered with 0.020 in. of cadmium during irradiation.

The cadmium ratios for the ML-1 operating core are shown in Figure 74. Three types of values are listed: values in positions marked with an asterisk were measured experimentally; values with three digits were obtained from 120 degree symmetry of the core; and values identified by $\sim$ were estimated from the values at the surrounding core portions.

The core cadmium ratio values were used to calculate the average cadmium ratio for the entire core. The value developed by this calculation was 3.9; this means that, on the average, about 26% of the power is epi-cadmium power. But since the cadmium ratios vary between 2.54 and 4.58, the percentage of epi-cadmium power production in an element ranges from 39% in the core center to 22% in some locations on the core periphery.

H. MISCELLANEOUS REACTIVITY MEASUREMENTS

Three methods were used to determine the various reactivity worths. The first used control blade calibration curves; control rod positions were noted before and after a perturbation. Comparison of the blade worths for the two positions gave a direct measure of the reactivity worth of the perturbation (the addition of poison, an experimental element, etc.).

The second method used was the rod-drop technique. In this method all rods are instantly inserted into the core and the total worth of the insertion determined. This is repeated with a perturbation introduced into the core. The difference between the rod worths is the worth of the perturbation.

The third technique is the period method. In this method, the reactor is made barely critical; one control rod is suddenly moved to a pre-determined position and the reactor period is noted. This procedure is repeated after causing a perturbation in the core and the excess reactivity

FIGURE 72. OPERATING POWER MAP GCRE-I REACTOR

FIGURE 73. OPERATING POWER MAP ML-1 REACTOR

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FIGURE 74. CADMIUM RATIOS IN THE ML-1 REACTOR

worth in the core is determined with the inhour equation.

1. Worth of the Upper Water Reflector in the GCRE Critical Assembly

The reactivity was measured as a function of height of the reflector (Figure 75). The experimental points shown reveal the difficulty of making this type of measurement (Ref. a).

2. Worth of Boron in the Flooded ML-1-IB Critical Assembly

Boron was added to the moderator in the flooded critical assembly in the form of chemically pure boric acid (Ref. d). It was found that the reactivity worth of the boron addition increased linearly in the range of 0 to 90 mg of boron per liter and that it was worth $1.76 \times 10^{-2} \Delta K/K$ per milligram of boron per liter.

It was observed that the boron was easily removed. After draining the borated water, the core was rinsed with demineralized water three times. The boron concentration of the third-rinse water was, within experimental error, the same as before boration.

3. Worth of Reactivity Shims in the ML-1 Reactor

Three types of reactivity shims were provided for use with the ML-1 reactor (Section II-E). The effect of these shims on the critical core loading is discussed in Section III-A-5. Measurements of the worth of one silver shim in six core positions in the ML-1 operating core were made for both the light and heavy silver shims. The replacement worths are presented graphically in Figure 76 as a function of ring number. The center element is considered to be ring one, the next six elements are in ring 2, etc. Peripheral elements are in ring 5.

I. MISCELLANEOUS POWER AND CADMIUM RATIO MEASUREMENTS

Power measurement experiments were performed with pin-type fuel elements in the ML-1-IA critical assembly and the ML-1-IB critical assembly to provide data for the design of the ML-1 reactor (Ref. c and d). The power produced in each pin of various non-uniformly loaded fuel elements was measured using removable fuel capsules. Five different fuel elements were used in these measurements. The characteristics of these experimental fuel elements are given in Table 7.

Results of the experiments are expressed as pin-to-pin power ratios. A pin-to-pin power ratio is defined as the ratio of the power produced per pin in one ring of pins to the power produced per pin in another ring. There are three rings in a 19-pin fuel element; ring 1 is the center fuel pin, ring 2 contains six fuel pins; and ring 3, the outer ring, contains 12 fuel pins. The ratio P_3/P_1 is therefore the ratio of the power per pin in the outer ring to that in the center pin.

The values of pin-to-pin power ratios determined during these experiments are given in Table 8. Values are given for the center core posi-

FIGURE 75. WORTH OF UPPER AXIAL REFLECTOR-GCRE CRITICAL ASSEMBLY

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FIGURE 76. WORTH OF REACTIVITY SHIMS IN THE ML-1 CORE

TABLE 7 - CHARACTERISTICS OF EXPERIMENTAL NON-UNIFORMLY LOADED FUEL ELEMENTS

Element Number	Reactor	Pin Loading (gm U-235)		Fuel Length (in.)	Pellet Diameter (in.)	Circle Diameter (in.)	Element Loading (gm U-235)
		Inner 7	Outer 12				
1	ML-1-IA Crit.	28.9	14.6	22.75	0.165	1.088	377.62
2	ML-1-IB Crit.	58.9	19.6	22.00	0.178	1.098	647.5
3	ML-1-IB Crit.	77.3	26.9	22.00	0.178	1.098	863.9
4	ML-1-IB Crit.	77.3**	26.9	22.00	0.178	1.098	786.6
5	ML-1-IB Crit.	77.3	19.6	22.00	0.178	1.098	776.3

* This is the distance between centers of diametrically opposite pins in the outer circle of 12.

**Center pin removed - 18 pin element

TABLE 8 - EXPERIMENTAL VALUES OF PIN-TO-PIN POWER RATIOS IN NON-UNIFORMLY LOADED ELEMENTS; CENTRAL CORE POSITION

Element Number*	Dry Core				Flooded Core			
	$(P_3/P_1)_{tot}$	$(P_2/P_1)_{tot}$	$(P_3/P_1)_{th}$	$(P_2/P_1)_{th}$	$(P_3/P_1)_{tot}$	$(P_2/P_1)_{tot}$	$(P_3/P_1)_{th}$	$(P_2/P_1)_{th}$
1	1.06	1.12	-	-	-	-	-	-
2	0.981	1.198	1.425	1.289	1.39	1.37	2.93	1.87
3	1.110	1.140	1.781	1.232	-	-	-	-
4**	0.950	-	1.378	-	-	-	-	-
5	0.869	1.184	1.367	1.325	-	-	-	-

* These elements are described by number in Table 7

**No center pin values are for P_3/P_2

tion only.

The experimentally determined effects of the two kinds of silver shims on pin-to-pin power ratios in the ML-1 (Ref. 28) are shown in Table 9.

TABLE 9 - PIN-TO-PIN POWER RATIOS IN THE SHIMMED ML-1 CORE

<u>Type Shim</u>	<u>$(P_3/P_2)_{tot}$</u>	<u>$(P_3/P_2)_{th}$</u>
None	1.05 ± 0.07	1.62 ± 0.16
"Light silver"	1.02 ± 0.07	1.57 ± 0.16
"Heavy silver"	0.97 ± 0.07	1.57 ± 0.15

The cadmium ratios for the five different elements described in Table 7 were determined. The cadmium ratio is defined as the ratio of total power to epi-cadmium power. The experimentally obtained values of cadmium ratios are given in Table 10 along with the cadmium ratios for the ML-1 elements. It was observed that flooding increased the cadmium ratio for all of these elements.

TABLE 10 - CADMIUM RATIOS IN NON-UNIFORMLY LOADED ELEMENTS
CENTRAL CORE POSITION

<u>Element No.*</u>	<u>Cadmium Ratios</u>	
	<u>Dry Core</u>	<u>Flooded Core</u>
1	--	--
2	3.33	3.14
3	2.57	--
4	2.80	--
5	2.74	--
ML-1	2.54	2.79

*These elements are described by number in Table 7.

J. EXPERIMENTAL MEASUREMENTS TO PROVIDE DATA FOR THE ML-1-II CORE DESIGN

Test operation of both the GCRE-I and the ML-1 first core (ML-1-I) indicated that uniform fuel loading would be a logical improvement for a second ML-1 core (ML-1-II). Experiments were performed to verify design calculations. The design parameters which were investigated were fuel pin loading and fuel pin diameter. Six fuel elements were provided for use in the experimental program in the ML-1 reactor (Table 11). Each of the six elements had 19 pins with 22 in. of active fuel length.

Measurements were made in three core positions: 5-E (the central core position); 6-F (a position halfway between the core center and the periphery); and 6-H (a peripheral position). Two types of measurements were made:

1) Replacement Reactivity Measurements: Measurements were made of the replacement reactivity for each element and of the power produced per pin in each element (ref. 29 and 30). Replacement reactivity is defined as the change in system reactivity resulting from the replacement of a standard ML-1 fuel element with an experimental element (Figure 77).

2) Pin-to-Pin Power Ratios: Both the total power and the epi-cadmium power produced in representative pins were measured in all experimental fuel elements (Ref. 31). This was accomplished by counting fission products in removable capsules after irradiating the elements. The power data were used to evaluate the pin-to-pin power ratios as described in the preceding section (Figure 78).

TABLE 11 - CHARACTERISTICS OF
UNIFORMLY LOADED EXPERIMENTAL ELEMENTS

IIc Element No.	Pin OD (in.)	Pellet Diameter (in.)	Loading of U ²³⁵ (gm)		
			Per Pin	Total per Element	Weight Above ML-1
1	0.280	0.215	38.0	722.0	-88.0
2	0.260	0.195	38.0	722.0	-88.0
3	0.250	0.177	75.0	1425.0	615.0
4	0.250	0.177	58.0	1102.0	292.0
5	0.250	0.177	26.6	505.4	-304.6
6	0.250	0.177	20.2	383.8	-426.2

K. PIN POWER MEASUREMENT BY CAPSULE TECHNIQUE

The last few years AGN has used the so-called "capsule technique" to measure the power produced in fuel pins. This technique consists of cutting a fuel pin of standard design into two long segments and one segment of between 1/2 and 1 in. length. The short segment is called the capsule and is taken from the center of the pin. Experimental elements are irradiated at low power and the capsule removed and counted. A series of capsule measurements is used to evaluate relative pin power, pin-to-pin power ratios, cadmium ratios, etc.

One difficulty with this technique arises from the need to hold the fuel rigidly in place. Usually epoxy or aluminum discs, or both, are used as spacer material, so that a power gap exists at the point of insertion of the spacers between the fuel pellets and the capsule. The effect of this gap is difficult to calculate, but it has been determined experimentally by placing a single UO₂ test pellet with an aluminum spacer at each end between two stacks of similar UO₂ pellets in a holder (Ref. 32). The holder was irradiated and counted with spacers of varying thickness inserted. The ratio of activity for a given spacer thickness versus activity for a single pellet was plotted (Figure 79).

FIGURE 77. REPLACEMENT REACTIVITY - UNIFORMLY LOADED ELEMENTS IN THE ML-1 REACTOR

- 0.177 inch DIA FUEL PELLETS
 ▲ 0.195 inch DIA FUEL PELLETS
 ■ 0.215 inch DIA FUEL PELLETS

FIGURE 78a. CORE POSITION 5-E

FIGURE 78b. CORE POSITION 6-F

FIGURE 78c. CORE POSITION 6-H

FIGURE 78. PIN-TO-PIN POWER RATIOS-UNIFORMLY LOADED ELEMENTS

FIGURE 79. ACTIVITY RATIO VERSUS SPACER THICKNESS

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18. Operating Core Determination for ML-1, Peak, R.D., AN-IDOP-29, 9 May 1961
19. GCRE Reactor Data, Lightle, R. E., unnumbered, dated 9 November 1960
20. Moderator Water and Gas Pressure Coefficients for ML-1, Peak, R.D., AN-IDOP-46, 11 June 1962
21. Preliminary Control Rod Calibration, Shield Water and Tungsten Baffle Reactivity Worths for ML-1, Mathews, D.R., and Peak, R.D., AN-IDOP-30, 17 April 1961
22. Final Control Rod Calibration, Shield Water and Tungsten Baffle Reactivity Worths for ML-1, Peak, R. D., AN-IDOP-34, 11 May 1961
23. Curve Fit of the ML-1 Control Rod Calibration for Shim Blade #2, Quilici, R.E., AN-FDD-199, undated
24. Power Distribution of Individual Fuel Elements in the IB-2L Core, Burgess, A.B., MEG-736, dated 13 January 1961
25. The ML-1-10 Flux and Power Mapping Experiment, Quilici, R. E., AN-AGCR-471, dated 28 February 1963
26. Experimentally Determined Axial Power Measurements of Individual Fuel Pin in the ML-1 Fuel Elements Under the Influence of Control Blades, Quilici, R.E., APMD-498, dated 28 December 1962
27. Pin-to-Pin Power Ratios in the Flooded ML-1 Core, Quilici, R.E., AN-AGCR-531, 17 May 1963
28. Shim Liner Effects on Individual Pin Power and Pin-to-Pin Power Ratios as Measured in the ML-1 Reactor, Quilici, R.E., APMD-504, dated 27 December 1962
29. Replacement Reactivity Worth of Experimental Elements, Worth of Central Fuel Elements in the Flooded ML-1 Reactor and Conduct of Experiment, Peak, R.D., AN-IDOP-41, 16 October 1961
30. IIC-Replacement Reactivity Measurements in the ML-1 Reactor, Quilici, R.E., AN-AGCR-30, dated 23 March 1962
31. IIC-Pin-to-Pin Power Ratio Measurements in the ML-1 Reactor, Quilici, R.E., AN-AGCR-335, dated 31 August 1962
32. Effects of Gaps on Measurements of Pin Power Using the Removable Capsule Technique, Quilici, R.E., APMD-667, 11 March 1963

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