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CAVITY REACTOR CRITICAL EXPERIMENT

Volume 1

by

G. D. Pincock, J. F. Kunze

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Nuclear Materials and Propulsion Operation

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GENERAL ELECTRIC COMPANY

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Final Report

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Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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ABSTRACT

A series of experiments were conducted at the Idaho Test Station on a large "cavity" reactor consisting of a cavity 183 cm in diameter of 122 cm long surrounded by 91 cm of heavy water. The cavity was fueled with uranium-235. Measurements were made on various configurations, including such variations as fuel diameter and shape, beryllium baffles in the reflector and insertion of various structural and operating materials characteristic of a nuclear rocket reactor.

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TABLE OF CONTENTS

		<u>Page</u>
1.0	INTRODUCTION	21
2.0	DESCRIPTION OF TEST ASSEMBLY AND TEST PROCEDURES	21
2.1	Reactor Description	21
2.2	Experimental Procedures	23
3.0	SUMMARY OF TEST RESULTS	31
3.1	Configurations and Critical Mass	31
3.2	Material Worth Measurements	31
3.3	Moderator Temperature Coefficient of Reactivity.	33
3.4	Power and Flux Distribution.	33
3.5	Catcher Foil Cadmium Ratios	34
3.6	Resonance Detector Data	35
3.7	Power Generation in Simulated Injection Tube and in Exhaust Nozzle	36
3.8	Neutron Lifetime Measurements	37
3.9	Fuel Analysis	37
4.0	CONFIGURATION 1 (0.89 Radius Ratio)	59
4.1	Initial Loading	59
4.2	Rod Calibration and Reactivity Measurements . .	63
4.3	Power Distribution Measurements	65
4.4	Resonance Detector Data - Gold Foils	67
5.0	CONFIGURATION 2 (0.465 and 0.53 Radius Ratios) . . .	104
5.1	Initial Loading	104
5.2	Rod Calibrations and Reactivity Measurements. .	105
5.3	Power Distribution Measurements	105
5.4	Resonance Detector Data - Gold Foils	106
6.0	CONFIGURATION 3A (0.67 Radius Ratio).	138
6.1	Initial Loading	138
6.2	Rod Calibration and Reactivity Measurements . .	138
6.3	Power Distribution Measurements	139
6.4	Resonance Detector Data	140

TABLE OF CONTENTS
(Continued)

	<u>Page</u>
7.0 CONFIGURATION 3B (0.67 Radius Ratio, End Plug Removed)	162
7.1 Plug Removal	162
7.2 Material Worth Measurements	162
7.3 Rod Worth Measurements	164
7.4 Reflector Temperature Coefficient of Reactivity	164
7.5 Power Distribution Measurements	165
7.6 Resonance Detector Data - Indium Foils	166
7.7 Neutron Lifetime Measurements	167
8.0 CONFIGURATION 9 - SIMULATED INJECTION TUBE .	193
8.1 Injection Tube Loading and Reactivity Worth . .	193
8.2 Unpoisoned Arrangement	193
8.3 Cadmium Lined Fuel Injection Tube	194
8.4 Borated Stainless Steel Lined Injection Tube . .	197
9.0 CONFIGURATION 10 - SIMULATED EXHAUST NOZZLE	219
10.0 CONFIGURATION 4 (0.67 Radius Ratio, End Plug Removed, Be 0.8 cm from Cavity Wall)	225
10.1 Rod Worth and Reactivity Measurements	225
10.2 Power Distribution Measurements - Bare Catcher Foils	227
10.3 Resonance Detector Data - Gold Foils	227
11.0 CONFIGURATION 5 (0.67 Radius Ratio, End Plug Removed, Be 5.8 cm from Cavity Wall)	246
11.1 Configuration 5A (Heavy Fuel Loading)	246
11.2 Configuration 5B (Light Fuel Loading)	250
12.0 CONFIGURATION 6 (0.67 Radius Ratio, End Plug Removed, Be 10.8 cm from Cavity Wall) ,	271
12.1 Rod Worth and Reactivity Measurements	271
12.2 Power Distribution Measurements - Bare Catcher Foils	272
12.3 Resonance Detector Data - Gold Foils	273

TABLE OF CONTENTS
(Continued)

	<u>Page</u>
13.0	CONFIGURATION 7A (3 Zone Axial Loading) 292
13.1	Rod Worth and Reactivity Measurements 292
13.2	Power Distribution Measurements 293
14.0	CONFIGURATION 7B (2 Zone Axial Loading) 309
14.1	Rod Worth and Reactivity Measurements 309
14.2	Power Distribution Measurements 309
14.3	Neutron Lifetime Measurements 310
15.0	CONFIGURATION 7C (3 Zone Axial Loading, One Zone Off Center) 325
15.1	Rod Worth and Reactivity Measurements 325
15.2	Power Distribution Measurements 325
16.0	CONFIGURATION 8 (2 Zone Axial Loading, 20% more Fuel than Configuration 7B plus Boron Poison) 337
16.1	Rod Worth and Reactivity Measurements 337
16.2	Neutron Lifetime Measurements 338
17.0	REACTOR CALCULATIONS OF THE EXPERIMENTAL EFFECTS. 342
17.1	Cross Section Sets 342
17.2	Gamma-Neutron Production Cross Sections 342
17.3	One-Dimensional Diffusion Theory Codes 343
17.4	Transport Calculations 344
17.5	Two Dimensional Diffusion Theory 345
18.0	ANALYTICAL vs EXPERIMENTAL CORRELATION AND CONCLUSIONS 352
18.1	Critical Mass vs. Radius 352
18.2	Fractional Fuel Worth 352
18.3	Fuel Acentricity 353
18.4	Beryllium Reflector Sections in the D ₂ O 353
18.5	Beryllium vs Beryllium Oxide 354
18.6	Worth of Structural Rocket Chamber Lining 355

TABLE OF CONTENTS

(Continued)

	<u>Page</u>
18.7 Moderator Temperature Coefficient	355
18.8 Spectral Indices (Cadmium Ratios) in Reflector .	356
18.9 Neutron Lifetime	357
18.10 Hydrogen in Cavity Void	358
18.11 Two Dimensional Effects	359
18.12 Concluding Remarks	359
19.0 REFERENCES	371

TABLES

2.1 Effective Delayed Neutron Parameters	24
3.1 Summary of Configurations.	39
3.2 Control Rod Positions at Delayed Critical and for Power Distribution Measurements	40
3.3 Aluminum Weights within the Cavity	41
3.4 Calculated Aluminum in Reflector Tank	42
3.5 Summary of Fuel Worth Measurements	43
3.6 Material Worth Summary.	44
3.7 Summary of Power Distribution - Uniform Core Loading	45
3.8 Summary of Catcher Foil Cadmium Ratios	45
3.9 Summary of Thermal Flux Distribution	46
3.10 Summary of Au Foil Cadmium Ratios	47
3.11 Injection Tube and Exhaust Nozzle Power Measurements	47
4.1 Fuel Tray Loading - Configuration 1	72
4.2 Inverse Multiplication - Configuration 1	73
4.3 Fuel Loading at Criticality - Configuration 1	74
4.4 Subcritical Rod Shape Data - All Rods	75
4.5 Subcritical Rod Shape Data - Actuator 4	76
4.6 Tabular Rod Worth - Actuator 4	77
4.7 Tabular Rod Worth - All Rods	78
4.8 Reactivity Measurements - Configuration 1	79
4.9 Fuel Worth - Configuration 1	80

TABLE OF CONTENTS

(Continued)

		<u>Page</u>
	Tables (Continued)	
4.10	Reactivity Effect of Table Separation Near Closed Position - Configuration 1	80
4.11	Catcher Foil Data - Configuration 1	81
4.12	Catcher Foil Cadmium Ratios - Configuration 1	84
4.13	Gold Foil Data - Configuration 1	85
4.14	Power Normalization Factors - Configuration 1	88
4.15	Gold Foil Cadmium Ratios and Thermal Neutron Flux - Configuration 1	89
5.1	Inverse Multiplication - Configuration 2.	108
5.2	Rod Worth and Excess Reactivity - Configuration 2.	111
5.3	Critical Fuel Tray Loading Arrangement - Configuration 2B.	112
5.4	Fuel Worth Measurements - Configuration 2	113
5.5	Catcher Foil Data - Configuration 2	114
5.6	Catcher Foil Cadmium Ratios - Configuration 2	118
5.7	Gold Foil Data - Configuration 2.	119
5.8	Power Normalization Factors - Configuration 2	121
5.9	Gold Foil Cadmium Ratios and Thermal Neutron Flux - Configuration 2	122
6.1	Critical Fuel Tray Loading Arrangement - Configuration 3A.	142
6.2	Catcher Foil Data - Configuration 3A	143
6.3	Catcher Foil Cadmium Ratios - Configuration 3A.	145
6.4	Gold Foil Data - Configuration 3A	146
6.5	Power Normalization Factors - Configuration 3A.	148
6.6	Gold Foil Cadmium Ratios and Thermal Neutron Flux - Configuration 3A	149
7.1	Critical Fuel Tray Loading Arrangement for Configuration 3B	169
7.2	Fuel Worth During Excess Reactivity Increase for Moderator Temperature Coefficient	170
7.3	Rod Worth Measurements - Configuration 3B.	170
7.4	Fuel Tray Loading for Reflector Temperature Coefficient Measurement.	171

TABLE OF CONTENTS
(Continued)

	<u>Page</u>
Tables (Continued)	
7.5 Moderator Temperature Coefficient of Reactivity - Configuration 3B	172
7.6 Catcher Foil Data - Configuration 3B	173
7.7 Indium Foil Data - Configuration 3B.	175
7.8 Power Normalization Factors - Configuration 3B.	177
7.9 Gold and Indium Foil Comparison in Reflector - Configurations 3A and 3B	178
7.10 Indium Foil Cadmium Ratios and Thermal Neutron Flux - Configuration 3B	179
7.11 Neutron Lifetime Measurements - Configuration 3B	180
8.1 Catcher Foil Data - Configuration 9 - Unpoisoned	198
8.2 Catcher Foil Data - Configuration 9 - 0.0508 cm Cd	200
8.3 Catcher Foil Data - Configuration 9 - 0.0254 cm Cd	202
8.4 Catcher Foil Data - Configuration 9 - 0.1524 cm Borated Stainless Steel.	204
9.1 Catcher Foil Data - Configuration 10	221
10.1 Critical Fuel Tray Loading Arrangement - Configuration 4.	230
10.2 Catcher Foil Data - Configuration 4	231
10.3 Gold Foil Data - Configuration 4.	232
10.4 Power Normalization Factors - Configuration 4	234
10.5 Gold Foil Cadmium Ratios - Configuration 4	235
10.6 Thermal Neutron Flux - Configuration 4	236
11.1 Catcher Foil Data - Configuration 5A	254
11.2 Gold Foil Data - Configuration 5A	255
11.3 Power Normalization Factors - Configuration 5A.	257
11.4 Gold Foil Cadmium Ratios and Thermal Neutron Flux - Configuration 5	258
11.5 Critical Fuel Tray Loading Arrangement - Configuration 5B.	259
11.6 Cadmium Ratios in Void Region - Configuration 5B Reduced Loading	260
11.7 Cadmium Ratios in Void Region with 0.3175 cm Al and 1.2 cm Water.	261

TABLE OF CONTENTS

(Continued)

	<u>Page</u>
Tables (Continued)	
12.1 Critical Fuel Tray Loading Arrangement - Configuration 6	276
12.2 Catcher Foil Data - Configuration 6	277
12.3 Gold Foil Data - Configuration 6	278
12.4 Power Normalization Factors - Configuration 6	281
12.5 Gold Foil Cadmium Ratios and Thermal Neutron Flux - Configuration 6	282
13.1 Fuel Tray Loading Arrangement - Configuration 7A. . .	295
13.2 Catcher Foil Data - Configuration 7A.	297
13.3 Catcher Foil Cadmium Ratios - Configuration 7A	299
14.1 Fuel Tray Loading Arrangement - Configuration 7B. . .	312
14.2 Catcher Foil Data - Configuration 7B.	314
14.3 Catcher Foil Cadmium Ratios - Configuration 7B	316
14.4 Neutron Lifetime Measurements - Configuration 7B . . .	317
15.1 Catcher Foil Data - Configuration 7C.	327
15.2 Catcher Foil Cadmium Ratios - Configuration 7C	329
15.3 Catcher Foil Cadmium Ratio Comparison - Configurations 7A and 7C	330
16.1 Fuel Tray Loading Arrangement - Configuration 8. . . .	339
16.2 Boron Carbide Control Rod Locations in Cavity - Configuration 8	340
16.3 Neutron Lifetime Measurements - Configuration 8. . . .	341
17.1 NMPO Nuclear Data Tape Energy Structure	346
17.2 20 Level Cross Sections of Principal Reactor Materials.	347
18.1 Effects of Fuel Cavity Liner on System Reactivity	361
18.2 Prompt Neutron Lifetime	361
18.3 Table Separation Reactivity Effects.	361

TABLE OF CONTENTS
(Continued)

	<u>Page</u>
FIGURES	
2.1	Cavity reactor critical experiment assembly 26
2.2	Core structure 27
2.3	Dolly and core assembly 28
2.4	Cavity reactor layout - configuration 2 29
2.5	Control rod distribution layout. 30
3.1	Summary of configurations. 48
3.2	Summary of configurations. 49
3.3	Fuel radius effects on fuel mass and density 50
3.4	Fuel worth vs critical mass and fuel radius. 51
3.5	Radial power distribution comparison at axial center of core - configurations 1, 2 and 3A. 52
3.6	Radial power distribution comparison at axial center of core - configurations 4, 5 and 6 53
3.7	Axial power profile, configuration 7A 54
3.8	Axial power profile, configuration 7C 55
3.9	Axial power profile, configuration 7B 56
3.10	Thermal neutron flux distribution radially through axial center of core - configuration 1 57
3.11	Thermal neutron flux distribution axially through radial center of core - configuration 1 58
4.1	Fuel tray installation pattern and nomenclature. 90
4.2	Initial fuel loading recipe for cavity reactor 91
4.3	Inverse multiplication curve, configuration 1, average of three channels 92
4.4	Relationship between the most probable and average path length for various values of variance 93
4.5	Subcritical rod worth curves - configuration 1 94
4.6	Radial power profile from bare catcher foils - configuration 1 95
4.7	Axial power profile from bare catcher foils - configuration 1 96
4.8	Radial power profile from bare catcher foil showing effects of position on a tray surface - configuration 1 97

TABLE OF CONTENTS (Continued)

		<u>Page</u>
	Figures (Continued)	
4.9	Radial distribution of bare gold foil activity in the cavity at an axial position of 151.1 cm - configuration 1	98
4.10	Axial distribution of bare gold foil activity in the cavity at core center - configuration 1	99
4.11	Bare gold foil activity distribution in the reflector - configuration 1	100
4.12	Gold cadmium ratios in the radial and end reflectors - configuration 1	101
4.13	Thermal neutron flux distribution radially through axial center of core - configuration 1	102
4.14	Thermal neutron flux distribution axially through radial center of core - configuration 1	103
5.1	Fuel tray arrangement - configuration 2	123
5.2	Fuel tray installation pattern and nomenclature - configuration 2A	124
5.3	Inverse multiplication curve - configuration 2 - average of three channels	125
5.4	Fuel tray installation pattern and nomenclature - configuration 2B	126
5.5	Radial power profile from bare catcher foils at an axial position of 151.1 cm - configuration 2.	127
5.6	Axial power profile from bare catcher foils at core center - configuration 2	128
5.7	Axial power profile over fuel gap due to aluminum support tube - configuration 2	129
5.8	Catcher foil cadmium ratio radial profile at an axial position of 151.1 cm - configuration 2.	130
5.9	Catcher foil cadmium ratio axial profile at core center - configuration 2	131
5.10	Radial distribution of bare gold foil activity in the cavity at an axial position of 151.1 cm - configuration 2.	132
5.11	Axial distribution of bare gold foil activity in the cavity at core center - configuration 2	133
5.12	Bare gold foil activity distribution in the reflector - configuration 2	134
5.13	Gold cadmium ratios in the radial and end reflectors - configuration 2	135

TABLE OF CONTENTS (Continued)

		<u>Page</u>
	Figures (Continued)	
5.14	Thermal neutron flux distribution radially through axial center of core - configuration 2	136
5.15	Thermal neutron flux distribution axially through radial center of core - configuration 2	137
6.1	Fuel tray installation pattern and nomenclature - configuration 3A.	150
6.2	Configuration 3A fuel loading arrangement	151
6.3	Radial power distribution from bare catcher foils - configuration 3A	152
6.4	Axial power distribution from bare catcher foils at core center - configuration 3A	153
6.5	Catcher foil cadmium ratio radial profile at an axial position of 151.1 cm - configuration 3A	154
6.6	Catcher foil cadmium ratio - axial profile at core center - configuration 3A.	155
6.7	Radial distribution of bare gold foil activity in cavity at an axial position of 151.1 cm - configuration 3A	156
6.8	Axial distribution of bare gold foil activity in the cavity at core center - configuration 3A	157
6.9	Bare gold foil activity distribution in the reflector - configuration 3A	158
6.10	Gold cadmium ratios in the radial and end reflectors - configuration 3A	159
6.11	Thermal neutron flux distribution radially through axial center of core - configuration 3A	160
6.12	Thermal neutron flux distribution axially through radial center of core - configuration 3A	161
7.1	Reflector temperature coefficient and reactivity - configuration 3B	181
7.2	Radial power profile from bare catcher foils at an axial position of 151.1 cm - configuration 3B	182
7.3	Axial power profile from bare catcher foils at core center - configuration 3B	183
7.4	Power distribution across reflector void at separation plane from bare catcher foils - configuration 3B	184
7.5	Effects on radial power at separation plane due to removing (30.5 cm) diameter plug - bare catcher foil data	185

TABLE OF CONTENTS

(Continued)

		<u>Page</u>
	Figures (Continued)	
7.6	Axial distribution of bare indium foil activity in the cavity at core center	186
7.7	Bare indium foil activity distribution in the reflector - configuration 3B.	187
7.8	Indium cadmium ratios in the radial and end reflectors - configuration 3B.	188
7.9	Thermal neutron flux distribution radially through axial center of core - configuration 3B	189
7.10	Thermal neutron flux distribution axially through radial center of core - configuration 3B	190
7.11	Typical results from neutron lifetime measurements - reactor at 2.61 dollars subcritical.	191
7.12	Pulse neutron generator - exponential decay results - reactor at 5.49 dollars subcritical.	192
8.1	Radial power distribution from bare catcher foils in injection tube - configuration 9 - unpoisoned	206
8.2	Axial power distribution from bare catcher foils in injection tube - configuration 9 - unpoisoned	207
8.3	Radial power distribution at separation plane from bare catcher foils - configuration 9	208
8.4	Axial power distribution from bare catcher foils at center of core - configuration 9 - unpoisoned	209
8.5	Axial power distribution from bare catcher foils in injection tube - configuration 9 with 0.0508 cm Cd . . .	210
8.6	Radial power distribution at separation plane from bare catcher foils - configuration 9 with 0.0508 cm Cd . . .	211
8.7	Axial power distribution from bare catcher foils at center of core - configuration 9 with 0.0508 cm Cd. . .	212
8.8	Axial power distribution from bare catcher foils in injection tube - configuration 9 with 0.0254 cm Cd . . .	213
8.9	Radial power distribution from bare catcher foils in injection tube - configuration 9 with 0.0254 cm Cd . . .	214
8.10	Axial power distribution from bare catcher foils at center of core - configuration 9 with 0.0254 cm Cd. . .	215
8.11	Axial power distribution from bare catcher foils in injection tube - configuration 9 with 0.1524 cm SS . . .	216
8.12	Radial power distribution from bare catcher foils in injection tube - configuration 9 with 0.1524 cm SS . . .	217

TABLE OF CONTENTS
(Continued)

	<u>Page</u>
Figures (Continued)	
8.13 Axial power distribution from bare catcher foils at center of core - configuration 9 with 0.1524 SS.	218
9.1 Axial power distribution from bare catcher foils in exhaust nozzle - configuration 10	222
9.2 Radial power distribution from bare catcher foils in exhaust nozzle - configuration 10	223
9.3 Axial power distribution from bare catcher foils at center of core - configuration 10	224
10.1 Radial power distribution from bare catcher foils at an axial position of 151.1 cm - configuration 4	237
10.2 Axial power distribution from bare catcher foils at core center - configuration 4	238
10.3 Radial distribution of bare gold foil activity at the cavity at an axial position of 151.1 cm - configuration 4	239
10.4 Axial distribution of bare gold foil activity in the cavity at core center - configuration 4	240
10.5 Bare gold foil activity distribution in the reflector - configuration 4	241
10.6 Bare gold foil and wire activity distribution in the radial reflector - configuration 4	242
10.7 Gold cadmium ratios in the radial and end reflectors - configuration 4	243
10.8 Thermal neutron flux distribution radially through axial center of core - configuration 4	244
10.9 Thermal neutron flux distribution axially through radial center of core - configuration 4	245
11.1 Radial power distribution from bare catcher foils at an axial position of 151.1 cm - configuration 5	262
11.2 Axial power distribution from bare catcher foils at core center - configuration 5A	263
11.3 Radial distribution of bare gold foil activity at an axial position of 151.1 cm - configuration 5A	264
11.4 Axial distribution of bare gold foil activity at the core center - configuration 5A	265
11.5 Bare gold foil activity distribution in the reflector - configuration 5A	266

TABLE OF CONTENTS
(Continued)

	<u>Page</u>
Figures (Continued)	
11.6 Relative bare gold foil and wire activity in the radial reflector - configuration 5A.	267
11.7 Gold cadmium ratios in the radial and end reflectors - configuration 5.	268
11.8 Thermal neutron flux distribution radially through axial center of core - configuration 5.	269
11.9 Thermal neutron flux distribution axially through radial center of core - configuration 5.	270
12.1 Radial power distribution from bare catcher foils at an axial position of 151.1 cm - configuration 6	283
12.2 Axial power distribution from bare catcher foils at core center - configuration 6	284
12.3 Radial distribution of bare gold foil activity at an axial position of 151.1 cm - configuration 6	285
12.4 Axial distribution of bare gold foil activity at the core center - configuration 6	286
12.5 Bare gold foil activity distribution in the reflector - configuration 6.	287
12.6 Relative bare gold foil and wire activity in the radial reflector - configuration 6	288
12.7 Gold cadmium ratios in the radial and end reflectors - configuration 6.	289
12.8 Thermal neutron flux distribution radially through axial center of core - configuration 6.	290
12.9 Thermal neutron flux distribution axially through radial center of core - configuration 6	291
13.1 Fuel tray installation pattern - configuration 7A - region 1	300
13.2 Fuel tray installation pattern - configuration 7A - region 2	301
13.3 Fuel tray installation pattern - configuration 7A - region 3	302
13.4 Radial power distribution from bare catcher foils - configuration 7A	303
13.5 Radial power distribution from bare catcher foils - configuration 7A	304

TABLE OF CONTENTS
(Continued)

	<u>Page</u>
Figures (Continued)	
13.6 Radial power distribution from bare catcher foils - configuration 7A	305
13.7 Axial power distribution from bare catcher foils - configuration 7A	306
13.8 Catcher foil cadmium ratio radial profile - configuration 7A.	307
13.9 Catcher foil cadmium ratio axial profile at radial center - configuration 7A	308
14.1 Fuel tray installation pattern - configuration 7B - region 1	318
14.2 Fuel tray installation pattern - configuration 7B - region 2	319
14.3 Radial power distribution from bare catcher foils - configuration 7B	320
14.4 Radial power distribution from bare catcher foils - configuration 7B	321
14.5 Axial power distribution from bare catcher foils - configuration 7B	322
14.6 Catcher foil cadmium ratio radial profile - configuration 7B	323
14.7 Catcher foil cadmium ratio axial profile at radial center - configuration 7B	324
15.1 Fuel tray installation pattern - configuration 7C - region 3	331
15.2 Radial power distribution from bare catcher foils - configuration 7C	332
15.3 Radial power distribution from bare catcher foils - configuration 7C	333
15.4 Radial power distribution from bare catcher foils - configuration 7C	334
15.5 Radial power distribution from bare catcher foils - configuration 7C	335
15.6 Axial power distribution from bare catcher foils - configuration 7C	336
17.1 Cavity reactor - effect of reflector thickness on k-eff - one dimensional spherical calculation.	350

TABLE OF CONTENTS

(Continued)

		<u>Page</u>
	Figures (Continued)	
17.2	Cavity reactor - sphere ₃ to cylinder shape factor - volume of $3.2 \times 10^6 \text{ cm}^3$	351
18.1	Comparison of NMPO and Los Alamos cavity reactors on basis of critical mass and ratios of fuel to cavity radius.	362
18.2	Effects of beryllium on fuel worth	363
18.3	Effects of off-center shift of fuel	364
18.4	Comparison of calculated vs measured effects of Be location in D_2O	365
18.5	Relative gold foil activity vs Be position in reflector . .	366
18.6	Comparison of temperature coefficients.	367
18.7	Gold cadmium ratios in the all D_2O reflected configura- tion	368
18.8	Zero power transfer function	369
18.9	Thermal flux distribution effects with hydrogen in cavity	370

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1.0 INTRODUCTION

In mid April 1966, a series of critical experiments was started at the Low Power Test Facility (LPT) in Idaho by the General Electric Company under contract with the National Aeronautics and Space Administration, Lewis Research Center. The experiments were performed on a mockup Cavity Reactor which contained a central cavity region 182.88 cm in diameter by 121.92 cm long surrounded by a 88.90 cm thick cylinder of D_2O . The D_2O covered both ends of the cavity as well as the radial region. One end reflector was mounted on a movable dolly which was remotely controlled.

Various configurations were tested to determine critical mass versus fuel radius within the cavity. Power distribution and resonance foil activation measurements were made on most configurations to determine power and flux distributions in the cavity and reflector-moderator regions. Both injector tube and exhaust nozzles were simulated to determine reactivity effects and power levels within the injector tubes and exhaust nozzle. A simulated heat shield and flow baffle in the form of beryllium was placed in the radial reflector and measurements were made to determine its effects at three distances from the cavity wall. Variable fuel loadings were also studied. In addition to power distribution and flux measurements; neutron lifetime was measured on three of the assemblies using the pulsed neutron method, the moderator temperature coefficient of reactivity was obtained up to $71^\circ C$ on a single configuration, and many reactivity measurements were obtained on various reactor core constituents.

Other experimental work has been done on the cavity reactor concept by the Los Alamos Scientific Laboratories⁽⁹⁾. The reactor used D_2O in the reflector which was 50.80 cm thick surrounding a cavity 101.60 cm long by 101.60 cm in diameter.

2.0 DESCRIPTION OF TEST ASSEMBLY AND TEST PROCEDURES

2.1 Reactor Description

The cavity reactor consisted of two aluminum tank assemblies as shown in Figure 2.1. The main tank contained the central void or cavity region which was 182.88 cm in diameter and 121.92 cm long. The tanks were water tight and were filled with heavy water (D_2O). The radial cavity wall was 0.9525 cm thick Al and the ends of the cavity were 1.270 cm thick Al. The D_2O thickness within each tank was 88.90 cm. A total of 83 kilograms of Al* alloy containing 331 grams of manganese impurity formed the structure inside the cavity for fuel support. There were 764 kilograms of structural aluminum, representing 1.2% volume fraction, inside the D_2O tanks. Part of this internal structure in the main tank provided rail support for 10.16 cm thick beryllium slabs used to simulate a heat shield in the radial reflector. The end reflector of the main tank contained thirty-six 2.093 cm diameter holes for control

* The aluminum mass within the cavity was increased slightly for configurations subsequent to the first.

rods. These holes represented 1% void in the end reflector. Electrical heating straps around both tanks provided the heat source for moderator temperature coefficient measurements. The D₂O temperature was monitored by three thermocouples in each tank. The thermocouples were located near the top, center and bottom of each tank.

The D₂O nominally contained $0.22 \pm 0.01\%$ H₂O. The H₂O concentration was monitored several times during the experiment with no indicated change. An argon atmosphere was maintained over the D₂O in each tank at all times to prevent contamination.

The fuel used for the experiment was in the form of solid sheets, 0.00254 cm thick. The uranium* contained 93.2% U-235, 1.0% U-234, 5.4% U-238 and 0.4% U-236. The fuel sheets were normally 7.303 cm square and had a fluoride plastic coating that was nominally 0.1% of the total weight. The fuel sheets weighed on the average of 2.62 ± 0.06 gm per sheet. Some larger sheets were used which were 1.5 times the length but the same width and thickness as the square sheets. The fuel was supported on corrugated aluminum screens or sheets which were held in place by structural support members inside the cavity. This arrangement is illustrated in Figures 2.2 and 2.3. The fuel tray spacing was changed after Configuration 1 testing to give more overlap of the trays. This change is shown in Figure 2.4 (See also Figure 5.1, Section 5.0).

Reactivity control was provided by as many as 36 B₄C control rods. There were 12 actuators, each of which contained a maximum of three control rods as shown in Figure 2.5. The actuator stroke was 86.26 cm and the ends of the rods were about 2.54 cm from the cavity wall when fully inserted. There was a 5.08 cm steel plug in the end of each rod, placing the active part of the rod about 7.62 cm from the cavity wall when fully inserted, and completely removing the rod from the D₂O when fully withdrawn. The control rod dimensions were as follows:

Diameter (overall)	1.905 cm
Stainless steel wall thickness	0.124 cm
Active rod length	76.20 cm

Each actuator had both shim and safety functions. The control rods were magnetically latched to the actuator drive. A scram signal released the magnet and the rods were driven in by spring force. The table separation provided additional safety over that contained in the control rods.

Because of the low excess reactivity associated with the experiments, it was not necessary to use the complete control system. A maximum of seven actuators and 20 control rods were used. These provided the required 2 dollar shutdown in all instances, and gave a total control system worth of 5 to 6%Δk.

*The uranium fuel contained a total impurity content of $3.2 \pm 0.5\%$.

2.2 Experimental Procedures

Control rod positions were monitored by a digital voltmeter located in the control room. The voltmeter or ratiometer would read from 0 to 9999 digits. The normally fully inserted rod position gave a reading of about 100 digits and the fully withdrawn position was about 9800 digits giving 112.3 digits per cm of rod travel. Rod worths were normally determined by the "rod bump" method. This procedure involved pulling one or more rods a fraction of the full travel. The increment pulled was governed by the period limitation. The total worth of the rod or rods pulled was extrapolated by dividing the reactivity worth of the increment pulled by the fraction of total worth represented by the rod travel as determined from previously measured rod worth curves. Rod worth curves were obtained early in the experiment, as will be discussed in subsequent sections.

All period measurements were reduced to reactivity by using the normal inhour equation. The effective delayed neutron parameters used in this equation are given in Table 2.1. The ratio of β_{eff}/β for the neutrons originating from the fuel was calculated to be 1.036. However, because of the uncertainty associated with the delayed neutrons emitted from the (γ -n) reaction in the D_2O , the overall β_{eff}/β was assumed to be 1.0 for this system. The value of the dollar used throughout the experiment in computing measured reactivity differences is 0.0076, with an estimated uncertainty of ± 0.0002 . The neutron generation time was assumed to be 4.0 milliseconds.

Determination of the asymptotic period was complicated by the very long lived component of the (γ -n) source in the heavy water. This source increased as the fission product inventory in the fuel increased. Previous studies of this effect have shown that measurements of reactor period taken over two successive decades, beginning at least 1 decade above the reactivity insertion level, can be extrapolated satisfactorily to an asymptotic period by a geometric progression of the differences.⁽²⁾ These corrections were usually zero at the beginning of a day's operation, and never exceeded 0.1% of the measured reactivity value after significant operation. Because of the methods of applying corrections to the measurements for the effects of these long-lived delayed neutrons, approximately 0.0001 of the total neutrons (last 5 groups in Table 2.1) are not included as contributors toward the system reactivity.

Power distribution measurements were made with catcher foils. These measurements were obtained by placing a 1.429 cm diameter aluminum foil in direct contact with a bare 1.429 cm diameter foil of highly enriched uranium. These two foils were then placed inside an aluminum bucket and cover assembly and mounted in the reactor for exposure. All foil exposures were for 20 minutes and after exposure in the reactor the activity from the fission products embedded in the aluminum foil from the uranium was counted in a beta scintillation counter. The counting system could count as many as six foils at a time. Each foil was counted in three of the counters and the average of the three counts was used for plotting. The foils were not counted against time but against a preset count on a normalizer foil. This eliminated the need

for decay correcting the individual foils. The foils were always normalized to 100,000 counts on the normalizer. The normalizers consisted of seven foils which were exposed at the same point in the reactor for each run. This point was at the separation plane about 15 cm from the cavity wall on the main tank. Seven foils were used so that a foil could be placed in the decay corrector counting head and in each of the other six foil counting heads to check counter alignment before counting the power distribution foils. These normalizer foils were also counted against time so that any foil could be corrected to a specific count rate at a given time after shutdown, if desired.

TABLE 2.1
Effective Delayed Neutron Parameters

<u>Group</u>	<u>β_i</u>	<u>λ_i</u>
1	.000210	.012400
2	.001410	.030500
3	.00127	.111000
4	.002550	.301000
5	.000740	1.100000
6	.000270	3.000000
7	.000780	.277000
8	.000240	.016900
9	.000084	.004810
10	.000040	.001500
11	.000025	.000428
12	.000028	.000117
13	.000004	.000044
14	<u>.000001</u>	.000004
	.007652	

Cadmium covered foils were mounted in the same fashion as the bare foils except cadmium buckets and covers were used. In all cases, 0.0508 cm thick cadmium was used. The reproducibility of the catcher foil technique is approximately $\pm 2\%$ standard deviation, not including counting statistics. This variance is probably due to the surface condition of the aluminum and the fuel.

Resonance foils were counted in a 256 channel gamma ray analyzer. The 0.41 Mev gamma peak was used to monitor the gold foil

activity and the 1.27 Mev gamma peak was used for indium. The resonance foil activities were corrected to absolute disintegration rates at shutdown by applying a conversion factor, K, to the foil activity at shutdown. This factor was based on the following values:

	<u>Au</u>	<u>In</u>
Branching ratio	0.9965	0.84
Peak/Total gamma ratio	0.720	0.362
Lucite and aluminum foil attenuation factor	0.872	0.923
Crystal efficiency factor	0.118	0.0165
Bias factor	0.825	0.950
Internal conversion factor	1.028	1.00057

The Au foils were counted at a distance of 3 cm from the crystal and the In foils were counted at a distance of 10 cm from the crystal.

The bias factor was determined from vendor-supplied standard foils.

The resulting conversion factors for Au and In were therefore:

$$K_{Au} = \frac{1}{(.9965/1.028) \times .720 \times .872 \times .118 \times .825} = 16.89$$

$$K_{In} = \frac{1}{(.84/1.00057) \times .362 \times .923 \times .0165 \times .95} = 227$$

Fig. 2.1 Cavity reactor critical experiment assembly

Fig. 2.2 Core structure

Fig. 2.3 Dolly and core assembly

Note: All dimensions are in centimeters

Fig. 2.4 Cavity reactor layout - configuration 2

Fig. 2.5 Control rod distribution layout

3.0 SUMMARY OF TEST RESULTS

3.1 Configurations and Critical Mass

This report covers all of the results from ten separate major configurations with some minor variations on three of the assemblies. A list of these configurations along with a brief description, fuel loading and excess reactivity values is shown in Table 3.1. The control rod positions at delayed critical and during power maps are summarized in Table 3.2. A cross section view of seven of these configurations and their variations is shown in Figures 3.1 and 3.2.

The cavity region contained a significant amount of aluminum as fuel support structure which varied somewhat for the first three core arrangements. The calculated amounts of aluminum are given in Table 3.3. Some of these values have been substantiated by measured weights. All of the configurations following Configuration 3 contained the same amount of aluminum as Configuration 3.

There was also a substantial amount of aluminum in the cavity wall and end plates. In addition, there was support structure within the D_2O regions. This material is summarized in Table 3.4.

The data obtained on Configurations 1, 2 and 3A plus subcritical data on smaller fuel radii produced sufficient information to show the relationship of critical mass versus ratio of fuel radius to cavity radius as shown in Figure 3.3. This figure refers to a gap-less configuration with a multiplication factor of approximately 1.02. This 2% Δk bias is due to the estimated reactivity worth of the gap and aluminum at the separation plane between the movable and fixed tanks.

The data point for Configuration 1, fuel to cavity radius ratio of 0.89, may be high by 5% to 10% because of the fuel distribution. This was the first configuration tested and a change was made to the fuel tray spacing following the testing of Configuration 1 that substantially reduced this problem. The data point at a fuel to cavity radius ratio of 0.465 was extrapolated from a subcritical level of about 4.2% Δk . The estimated uncertainty of this point is -1, +4 kg.

3.2 Material Worth Measurements

3.2.1 Fuel Worth

Fuel worth measurements for each of the configurations tested are summarized in Table 3.5. The volume weighted averages given here were based on a relative radial and axial fuel worth distribution equal to the power distribution from catcher foils.

Volume weighted average

$$= 2\pi \int_0^X \int_0^R W(r_1 X) r dr dx$$

where $W(r_1, X)$ = fuel worth at specific location from core center
 r = radius from cavity center
 x = distance from end of core

The power distribution data were normalized to the core center. Therefore, by multiplying the power distribution weighted average radial times the average axial and taking this product times the fuel worth at the core center, the volume weighted average fuel worth was obtained.* The fuel worth at the outer edge of the fuel was over the core length so represented an average axial. The volume weighted fuel average could, therefore, be obtained from the outer edge fuel worth by dividing the weighted average radial from the power distribution data by the peak relative power at the outer edge of the fuel and multiplying this by the fuel worth at the core edge. Both procedures were used and the average value calculated. These appear in Table 3.5 and the standard error represents the average error associated with the two fuel worth measurements. Precise measurements of the fuel worth toward the "corners" of the fuel region could not be made, and the over-all core average results are accordingly uncertain.

The relationship of reactivity change to critical mass and fuel radius is given in Table 3.5 for two configurations where the total fuel was increased uniformly over the fueled region as part of the required measurements. Such values can also be calculated where fuel worths are available, and these results are shown in Figure 3.4. The value for Configuration 2 at a 0.465 fuel to cavity radius ratio was extrapolated from the measured fuel worth data. The results prior to placing beryllium in the radial reflector, fall on a smooth curve. The data with Be in the reflector tend to be above the curve.

3.2.2 Other Material Worths

Other material worths were measured during the course of the experiment and these are summarized in Table 3.6. It will be seen from the beryllium worth values, that the reactivity penalty with beryllium placed 5.8[†] cm from the cavity wall was less than when beryllium was placed 0.8 cm or 10.8 cm from the cavity wall. The beryllium was 10.16 cm thick and was located in the radial reflector tank, completely surrounding the cavity. This apparent minimum reactivity loss with the beryllium around 5 cm was not expected, however, the indicated error does not conclusively prove the magnitude of the minimum. Comparing the fuel loading and k-excess values from Configurations 5B and 6, it would be concluded that with the beryllium located at 5.8 cm the reactor was more reactive by as much as 1.9% Δk than with the beryllium at 10.8 cm from the cavity wall. However, there was a significant difference in fuel loading (3 kg) between Configurations 5A and 5B indicating the possibility of a change in beryllium worth with fuel mass in the reactor.

* This procedure assumes a flat adjoint flux, which calculations confirmed to within 3%

† The beryllium locations of 0.8, 5.8, and 10.8 cm refer to the tangent to the slabs. The actual average thicknesses of D₂O between wall and slabs are 1.7, 6.7, and 11.7 cm.

3.2.3 Acentricity of Fuel

The fuel was shifted off-center over Region 3 on Configuration 7A. This assembly had a three region loading as follows

<u>Region</u>	<u>Diameter (cm)</u>	<u>Length (cm)</u>	<u>Relative Fuel Density</u>
1	122	61	1.0
2	85.4	30.5	0.83
3	70.1	30.5	0.73

Region 3 was re-positioned so that one side was directly in line with the outer surface of Region 2. This caused an increase in k -excess of $0.059 \pm 0.005\% \Delta k$. The off-center movement of a complete uniformly loaded core (Configuration 5) caused a reactivity change of $-0.0458 \pm 0.0142\% \Delta k$ for a 3.81 cm off-center movement and $-0.0984 \pm 0.0174\% \Delta k$ for a 7.62 cm movement. (Note these were decreases)

3.3 Moderator Temperature Coefficient of Reactivity

The D_2O surrounding the cavity was heated from $31.7^\circ C$ to $70.0^\circ C$ and the reactivity change was measured. Over this $38.3^\circ C$ temperature increase there was a loss of $0.442\% \Delta k$. This gives an average temperature coefficient of $-0.0115\% \Delta k / ^\circ C$ increase in temperature but the reactivity change was not linear with temperature. The temperature coefficient was about $-0.007\% \Delta k / ^\circ C$ at $38^\circ C$ and about $-0.022\% \Delta k / ^\circ C$ at $70^\circ C$. At $22^\circ C$, with Be at 5.8 cm, a positive $(0.013)\% \Delta k / ^\circ C$ was measured.

3.4 Power and Flux Distribution

Foil exposures within the cavity included bare and cadmium covered gold, indium, manganese, and catcher foils. Most of the measurements were with catcher foils and gold. Indium foils were used for Configurations 3B and 5 and manganese foils were used on Configuration 5. A summary of the bare catcher foil results from the uniformly loaded core is shown in Table 3.7. The radial power profiles at the axial center of the cavity from Configurations 1, 2 and 3A are presented in Figure 3.5. The effects of decreasing the fuel radius and increasing the fuel loading on power distribution are clearly shown here. The same power distributions on Configurations 4, 5 and 6 are given in Figure 3.6. There was very little difference between Configurations 4, 5 and 6 indicating essentially no effect due to moving the beryllium from 0.8 to 10.8 cm from the cavity wall. There were about 1775 gm more fuel in the reactor for Configurations 4 and 5 than for Configuration 6 which appears to be the reason for the higher power ratio at the edge of the fuel and in the void region for Configurations 4 and 5. The point at the outer edge of the fuel for Configuration 5 is low (by 4%) compared to the data across the void region between the fuel and D_2O tank. This point should agree more closely with Configuration 4, because of the two identical core loadings.

The power distributions for Configurations 7A, 7B and 7C are best summarized in graphic form. Configurations 7A and 7C are briefly described in Section 3.2. Configuration 7B was a two region loading as follows.

<u>Region</u>	<u>Diameter (cm)</u>	<u>Length (cm)</u>	<u>Relative Fuel Density</u>
1	122	61	1.0
2	110	61	0.667

Figure 3.7 shows the axial power profiles at the center and outer edge of the fueled regions. All axial plots are referenced to the inside or wet surface of the outer wall of the end reflector containing the control rods. The cavity begins at 90.1 cm from this reference point. The jagged distribution at the outer edge of the fuel is due to the three region loading. The indicated discontinuities are at the end of each region, the higher point being on the larger diameter section and the lower point being on the smaller diameter section where the two regions come together. The unusual axial profile at the center of the core reflects the varied fuel loading, the heaviest fuel concentration, and thus the greatest attenuation radially, being at the control rod end of the core and the lightest loading being at the separation plane where the power per unit fuel mass is the highest.

This same power distribution measurement was repeated with Region 3 shifted off center to coincide with Region 2 on one side (Configuration 7C). The resulting axials at the core center and outer edge of the fuel are shown in Figure 3.8. The open symbol data at the outer edge of the fuel were from the plane where Region 3 was lined up with Region 2 and the solid symbol results were 180 degrees from this plane in Region 3. The relative power in Regions 1 and 2 at the outer edge of the fuel both showed decreases due to shifting Region 3. This was apparently caused by the shielding effect of the position of Region 3 and/or by less shielding to the foils at the center of the core. The axial profile at the center of the core over these two regions was essentially unchanged except over Region 3 where there was a 4.8% increase. At the outer edge of the fuel in Region 3 where it was in line with Region 2, the point next to Region 2 showed a 14% increase while the other two points were unchanged. At 180 degrees from the plane where Regions 2 and 3 lined up, three data points are shown. The point nearest Region 2 decreased 32% due to the increased neutron shielding from Region 2. The point at the center of Region 3 decreased 1.7% and at the end of this region the point was 8.3% lower than before shifting this region. The precision of the foil positioning between the two runs probably accounts for some of the variation in results.

The relative axial power distributions at the center and outer edge of the fuel for Configuration 7B, the two region loading, are presented in Figure 3.9. The power gradients observed on this configuration were much less severe than for Configuration 7A principally because of the lighter overall fuel loading. A similar discontinuity occurs between Regions 1 and 2, but was less severe than for Configuration 7A.

3.5 Catcher Foil Cadmium Ratios

Catcher foil cadmium ratio data were obtained within the cavity from Configurations 1, 2 and 3A. These are briefly summarized in Table 3.8. The harder flux, caused by reducing the fuel radius and

increasing the fuel loading for these three configurations, is evident in the data shown in this table. Increasing the fuel loading a factor of 1.85 in going from Configuration 1 to Configuration 2 reduced the cadmium ratio at the core center to 0.42 of Configuration 1 and at the edge of the fuel the decrease was to 0.66 of Configuration 1.

The same comparison between Configuration 1 and 3A shows the cadmium ratio to be 0.68 of Configuration 1 at the core center and about the same at the outer edge of the fuel for a 32% increase in fuel loading. There is, of course, the effect of reduced fuel radius in these comparisons along with the change in fuel loading.

3.6 Resonance Detector Data

Resonance detector foils included primarily gold and indium. Both bare and cadmium covered foil data were obtained. These data were reduced to thermal fluxes and infinitely dilute cadmium ratios. The thermal fluxes quoted are for equivalent 2200 m/sec fluxes, and are 0.886 the value of the Maxwell-Boltzmann averaged flux at 20°C. A summary of the thermal flux values is shown in Table 3.9. The nominal standard error associated with these values is approximately 10%. Typical radial and axial thermal flux profiles for Configuration 1 are given in Figures 3.10 and 3.11, respectively. The flux peak in the D₂O occurs around 15 cm from the cavity wall in all cases. The thermal flux levels within the cavity varied significantly because of the different required fuel loadings. The reflector regions showed less variations due to configuration changes and the largest fuel radius gave the highest flux levels per watt of reactor power. The fluxes of Configuration 2 and 3A were about the same but their flux levels were from 11 to 14% lower, on the average, than Configuration 1. Removing the 30.5 cm diameter plug in the movable table increased the overall thermal flux level in the core by about 20% and decreased the level in the reflectors about 10%. This shift in neutron flux is believed to be due to streaming of neutrons from the 30.5 cm diameter void into the cavity from the peak flux region in the D₂O occurring about 15 cm from the cavity wall. Thus, removing the plug apparently caused an overall shift in the thermal neutron flux distribution in the D₂O as well as affecting the flux within the cavity, principally by increasing the flux in the vicinity of the plug.

Placing a 10.16 cm beryllium ring around the cavity in the radial reflector 0.8 cm from the outer surface of the cavity wall caused the thermal flux within the cavity to decrease about 40% below that measured for Configuration 3B. There was, however, a 43% increase in fuel loading required to maintain a critical assembly which caused a harder flux within the fueled region. In the radial reflector near the flux peak, the thermal flux level increased about 15%. This increased level continued to the outer edge of the reflector.

Moving the beryllium back to 5.8 cm from the cavity wall caused a slight (approximately 5%) increase in the thermal flux within the cavity compared to Configuration 4 although there was no change in fuel loading. There was an 8% average decrease in thermal flux in the radial reflector.

Placing the beryllium 10.8 cm from the cavity wall resulted in an 8% decrease in fuel loading compared to having the beryllium 0.8 cm from the cavity wall. Within the fueled region there was an increase in thermal flux of about 20% compared to Configuration 4. The thermal flux in the radial reflector decreased about 17% over Configuration 4 which is about twice the decrease with the beryllium 5.8 cm from the cavity wall.

Cadmium ratio data obtained from gold foils on Configurations 1, 2, 3A, 4, 5 and 6 are summarized in Table 3.10. All of these ratios are corrected for resonance self-shielding to infinitely dilute foil activities. Between Configurations 1 and 2, the significant changes occurred in the end reflector and cavity regions where there was a 20 to 25% decrease in cadmium ratios. The harder flux was due to the increased fuel loading. This harder spectrum appears in the end reflector because of its close proximity to the concentrated fuel in the cavity.

Configuration 3A compared to Configuration 1 showed the cadmium ratio to be about 14% lower within the fuel due to the reduced fuel radius and heavier fuel loading on Configuration 3A. In the void region, the cadmium ratio was unchanged. The cadmium ratios in the end reflector were, on the average, 13% lower than Configuration 1 whereas the radial reflector was unchanged.

Removing the end plug and placing 10.16 cm of Be 0.8 cm from the cavity wall in the radial reflector caused an average 14% decrease in cadmium ratio within the fueled region. There was a 48% increase in fuel loading between these two assemblies which accounts in part for the lower cadmium ratios. The radial and end reflectors showed about this same change near the cavity wall but little or no difference beyond about 15 cm into the reflectors.

There was no measureable change in cadmium ratio in the core between Configuration 4 and 5. Beyond about 35 cm in the radial reflector there was some indication of a slight reduction in cadmium ratio.

A 10 cm motion of the beryllium reflector between Configurations 4 and 6 coupled with an 8% difference in fuel loading caused the cadmium ratios in the fueled region to increase 7.5% on the average. This is considered to be due primarily to the difference in fuel and not the change in beryllium position. There was a definite decrease in cadmium ratio in the radial reflector. Ignoring the data scatter and using a smooth curve comparison, the ratio decreased about 10%. This was apparently due to the replacement of the D₂O moderator with beryllium near the peak flux location in the reflector. No significant change was observed in the end reflector.

3.7 Power Generation in Simulated Injector Tube and in Exhaust Nozzle

Configuration 9 was a mockup of a fuel injector tube. Various poisons were used to suppress the power in the tube. A total of 1209 gm of fuel was wrapped around a 3.81 cm diameter Al tube in a 5.08 cm diameter hole in the center of the end reflector. The measured power in this tube with respect to total core power is given in Table 3.11.

Configuration 10 was the simulated exhaust nozzle. This consisted of a 30.5 cm diameter hole in the end reflector. Three cylinders of Al were placed in this region on which fuel could be wrapped. These cylinders were 5.08, 10.16 and 20.32 cm in diameter. A total of 254 gm of fuel was dispersed over the nozzle region in making the measurement. The total power in the nozzle with respect to total core power is also given in Table 3.11.

3.8 Neutron Lifetime Measurements

Neutron lifetime was measured on Configurations 3B, 7B and 8. The values obtained in each case is given as follows:

<u>Configuration</u>	<u>Neutron Lifetime</u> <u>(milli sec.)</u>
3B	3.10 ± 0.05
7B	3.48 ± 0.06
8	2.56 ± 0.05

Each value represents an average of several measurements weighted by the calculated standard error of each measurement. Between Configuration 3B and 7B 10.16 cm of beryllium were placed around the cavity in the radial reflector at 5.8 cm from the cavity wall and the fuel loading was increased about 16%. Configuration 8 was the same as Configuration 7B except for a 20% increase in fuel loading and sufficient boron poison dispersed throughout the fuel region to compensate for the added reactivity. The addition of fuel and poison in the fueled region reduced the neutron lifetime 26.4%. Taking into account this effect of increased fuel loading and poison within the cavity, it was concluded that the 16% increase in fuel loading between Configurations 3B and 7B would have reduced neutron lifetime by about 12%. However, the net change in going to Configuration 7B from 3B was a 12% longer lifetime.

Keeping in mind that Configuration 3B was uniformly loaded and Configuration 7B had a variable loading which may have had some effect on neutron lifetime, it is still concluded, from the experiment, that beryllium alone increased neutron lifetime in the order of 25%.

3.9 Fuel Analysis

Following the reactor experiments reported herein, chemical analyses were performed on several samples of sheet fuel. The coated sheet fuel averaged $(96.8 \pm 0.5)\%$ uranium whereas uncoated sheets contained $(97.2 \pm 0.7)\%$ uranium. Two samples of cleaned, unoxidized fuel were also included in the analyses and these measured $(100.0 \pm 0.5)\%$ uranium. Virtually all coated fuel was used in the reactor indicating $(3.2 \pm 0.5)\%$ of the fuel weight was coating and oxygen.

In early 1966 six uncoated sheets of fuel were carefully weighed and wrapped in aluminum foil. After approximately one year, they were reweighed and the results showed an increase in weight of $(0.11 \pm 0.04)\%$. These samples would be expected to show only a small increase in weight due to oxidation as they were in a closed atmosphere.

During one of the configurations tested following these experiments the fuel weight increased 70 grams from a total fuel weight of 28.68 kg for a 0.24% increase. The time period between weights was one year. Configuration 1, however, showed a 50 gm decrease in fuel weight from the weights during initial loading to the final weights at the conclusion of the test 23 days later. Part of this weight difference is due to weighing errors.

In conclusion there is evidence that in spite of the fluorocarbon coating on the fuel, some oxidation does occur with time and oxygen and coating represents approximately 3% of the total weights reported in this report. Relative consistency in reported fuel loadings is nominally 0.5% total spread created by uncertainties in the amount of oxidation that occurred from the beginning to the end of the experiment.

NOTE, THROUGHOUT THE REPORT, ALL FUEL MASSES OF U^{235} OR ORALLOY (93% U^{235}) ARE QUOTED AS MEASURED DIRECTLY, AND THEREFORE INCLUDE A 3% NON-URANIUM IMPURITY CONTENT.

UF₆ AND MOCK-UP EXPERIMENTS

Following the experiments reported herein, a series of reactor tests were performed to determine the differences between an accurate mock-up using sheet fuel in the core and an actual UF₆ fueled reactor. The ratio of the fuel loading between the mock-up and the UF₆ reactors was 1.09 ± 0.02 . * Included in this value is the $(3.2 \pm 0.5)\%$ correction on the sheet fuel for oxidation and coating.

*"Cavity Critical Experiment Monthly Progress Report for the Period May 1, 1967, Through May 28, 1967," General Electric Company, NM&PO, ITS, June 2, 1967, (GEMP - 523)

TABLE 3.1
Summary of Configurations

Configuration	Ratio Fuel Radius to Cavity Radius	Fuel Loading ⁽⁴⁾ (kg)	k-excess (%Δk)	Further Description
1	0.89	11.0	0.213	30.5 cm end plug in reactor
2A	0.465	25.3 (estimated)		
2B	0.53	20.4	0.981	30.5 cm end plug in reactor
3A	0.67	14.5	0.0367	30.5 cm end plug in reactor
3B	0.67	15.0	0.087	30.5 cm end plug out of reactor
4	0.67	21.5	0.313	same as 3B, 10.16 cm Be in radial reflector at 0.8 cm from inner D ₂ O surface
5A	0.67	21.5	3.098	same as 4, Be at 5.8 cm
5B	0.67	18.5	0.621	same as 4, Be at 5.8 cm
6	0.67	19.7	0.983	same as 4, Be at 10.8 cm
7A (1)	0.67, 0.47, 0.38	28.4	1.570	radial reflector same as 5
7B (2)	0.67, 0.60	20.3	0.245	radial reflector same as 5
7C (3)	0.67, 0.47, 0.38	28.4	1.629	same as 7A, region 3 off-center
8	0.67, 0.60	24.4	0.110	same as 7B, extra fuel poisoned down with control rods.
9	0.67	14.6	0.862	same as 3B, 1209 gm fuel in injector tube simulation. No poison around nozzle
10	0.67	14.6	0.796	same as 3B, 254 gm of fuel in simulated exhaust nozzle

(1) This was a variable fuel loading in three regions. Refer to Section 13.0 for details.

(2) Refer to Section 14.0 for details.

(3) Refer to Section 15.0 for details.

(4) Mass of total fuel (Oralloy, 93.2% U²³⁵, 5.8% U²³⁸, 1% U²³⁶ plus a 3% impurity content).

TABLE 3.2

Control Rod Positions at Delayed Critical and for Power Distribution Measurements

Configuration	Delayed Critical (1)		Power Distribution	
	Actuator No.	Position (cm withdrawn)	Actuator No.	Position (cm withdrawn)
1	4	26	4	8
2B	6	0		
	4	22	6	39
3A	All rods withdrawn (k-excess by period measurement)		6	41
3B	All rods withdrawn (k-excess by period measurement)		6	32
4	6	21	6	24
5A	4,5,6	0	4,5,6	0
	3	13	2	23
	7	2	3	3
5B	7	4	1,2,3	65
6	1 to 6	31	6	11
7A	1 to 6	24	1 to 6	25
7B	1 to 6	53	4,5,6	41
7C	1 to 6	23	1 to 6	24
8	All rods withdrawn (k-excess by period measurement)			
9 (unpoisoned injection tube)	5	18	6	0
	6	8	5	34
10	6	0	--	--
	1	47	--	--

(1) Position of rods for k-excess values given in Table 3.1. Rods not listed are fully withdrawn.

TABLE 3.3
Aluminum Weights Within the Cavity

Configuration 1

494 screen surfaces	33.10 kg
screen support rails + welds	24.62
support rings	19.46
support tubes (pipe)	4.44
Al wires to hold fuel	1.61
	<u>83.23 kg</u>

Configuration 2 (0.53 radius ratio)

screen support rails	24.15 kg
support angles	3.96
support rings	19.46
support stubs	1.97
support tubes (pipe)	4.44
bolts	0.54
488 screen surfaces	22.70
40 solid surfaces	7.78
148 hold down straps	17.61
screen support tubes	6.76
	<u>119.37 kg</u>

Configuration 3

same as Configuration 2 plus 116	119.37kg
more hold down straps	13.80
	<u>133.17 kg</u>

TABLE 3.4
Calculated Aluminum in Reflector Tanks

<u>Fixed Tank</u>		<u>Weight-kg</u>
1.	End plate stiffeners	25.4
2.	Cavity support members	24.2
3.	Rod guide tubes	20.8
4.	Be support rings	54.6
5.	Cavity end plates	270.1
6.	Radial cavity wall	181.4
	Total	<u>576.5</u>
 <u>Movable Tank</u>		
1.	End plate stiffeners	89.9
2.	Tie rods	8.2
3.	Cavity end plate	270.1
	Total	<u>368.2</u>

D_2O volume = $2.80 \times 10^7 \text{ cm}^3$

Total Al volume within the reflector region = $3.48 \times 10^5 \text{ cm}^3$

TABLE 3.5
Summary of Fuel Worth Measurements

Configuration	Fuel Loading (kg)	Fuel Worths $-\% \Delta k / \text{gm}$		Volume Weighted Core Average
		Center of Cavity	Outer Edge of Fuel	
1	11.0	$(2.550 \pm 0.267) \times 10^{-3}$	$(3.420 \pm 0.267) \times 10^{-3}$	$(3.017 \pm 0.275) \times 10^{-3}$
2B	20.4	$(0.533 \pm 0.044) \times 10^{-3}$	$(1.575 \pm 0.019) \times 10^{-3}$	$(0.902 \pm 0.56) \times 10^{-3}$
3A	14.5	$(1.254 \pm 0.254) \times 10^{-3}$	$(2.455 \pm 0.297) \times 10^{-3}$	$(1.760 \pm 0.296) \times 10^{-3}$
3B	15.0	$(1.220 \pm 0.148) \times 10^{-3}$	$(2.188 \pm 0.132) \times 10^{-3}$	$(1.681 \pm 0.168) \times 10^{-3}$
4	21.5	$(0.483 \pm 0.076) \times 10^{-3} *$	$(1.401 \pm 0.072) \times 10^{-3}$	$(1.073 \pm 0.055) \times 10^{-3}$
5A	21.5	$(0.604 \pm 0.091) \times 10^{-3}$	$(1.643 \pm 0.050) \times 10^{-3}$	$(1.010 \pm 0.106) \times 10^{-3}$
6	19.7	$(0.656 \pm 0.086) \times 10^{-3}$	$(1.639 \pm 0.081) \times 10^{-3}$	$(1.074 \pm 0.113) \times 10^{-3}$
7B	20.4			$(0.831 \pm 0.055) \times 10^{-3}$
3B	15.0	$\Delta k / k / \Delta m / m = 0.243$ (average fuel loading of 16 kg for measurement)		
7B	20.4	$\Delta k / k / \Delta m / m = 0.170$		

* This value was determined to be low and was not used in the core average.

TABLE 3.6
Material Worth Summary

Configuration	Material	Material Location	Material Worth (%Δk)
1	Al	Top and center of Tray 9	$(-4.135 \pm 0.072) \times 10^{-5} / \text{gm}$
1	Void	0.952 cm gap at table separation	-0.525 ± 0.056 (1)
3A	Al	2.54 cm Al at table separation in fixed and movable tanks	-1.750 ± 1.221 (2)
3B	30.5 cm End Plug	Center of movable tank	0.698 ± 0.088
3B	Stainless Steel	Layer 0.0965 cm thick on inner surface of radial cavity wall	-8.68 ± 0.13
3B	Stainless Steel	Layer 0.193 cm thick on inner surface of radial cavity wall	-16.50 ± 0.25
4	Be	10.16 cm Be at 0.8 cm from cavity wall in radial reflector	-7.873 ± 0.343
5	Be	10.16 cm Be at 5.8 cm from cavity wall in radial reflector	-5.088 ± 0.351
5	BeO vs. Be	BeO replacing Be around the cavity at 5.8 cm from cavity wall	-2.055 ± 0.327
5	C	19 kg in void between fueled region and D ₂ O	-0.0797 ± 0.0100
*	H	2×10^{21} atom/cc in void region between fuel and D ₂ O	-11.62 ± 0.35
6	Be	10.16 cm Be at 10.8 cm from cavity wall in radial reflector	-5.298 ± 0.328
9	1209 gm fuel	In simulated injector tube	0.809 ± 0.054
9	0.0508 cm Cd	Around injector tube	-1.598 ± 0.050
9	0.0254 cm Cd	Around injector tube	-1.353 ± 0.061
9	0.152 cm B-SS (3)	Around injector tube	-0.973 ± 0.077
10	254 gm fuel	In simulated exhaust nozzle	0.636 ± 0.051

(1) Extrapolated from worth of smaller table movement

(2) Extrapolated from the worth of a 0.0812 cm thick Al plate in void at table separation plane.

(3) 1584 gm stainless steel with 0.7% by wt. natural boron.

* Measurement made on mockup UF₆ reactor.

TABLE 3.7

Summary of Power Distribution

Configuration	Radial-Ratio Fuel Edge to Core Center	Radial Weighted Avg. at Axial Center of Core	Axial Avg. at Radial Center of Core
1	1.19	1.079	1.036
2	2.84	1.540	1.165
3A	1.87	1.444	1.065
3B	1.83	1.310	1.124
4	2.27	1.398	1.208
5	2.13	1.359	1.185
6	2.10	1.375	1.191

All values are normalized to center of active core. The radial averages are from the center to outer edge of fuel.

TABLE 3.8

Summary of Catcher Foil Cadmium Ratios

Configuration	Center	Outer Edge of fuel at Axial Center	Control Rod End of Core at Radial Center	Separation Plane at Radial Center
1	22.3	27.0	25.1	24.0
2	9.4	17.8	15.4	13.3
3A	15.2	27.8	19.2	18.0

TABLE 3.9

Summary of Thermal Flux Distribution

Location		Thermal Neutron Flux Level Per Watt of Reactor Power Configuration						
Radial (cm)	Axial (cm)	1	2	3A	3B	4	5A	6
0	151.1	2.30	0.69	1.11	1.38 ⁽²⁾	0.80	0.73	0.94
30.5	151.1	--	1.05	--	--	0.95	1.09	0.94
45.7	151.1	--	--	--	--	--	--	1.10
61.0	151.1	2.42	--	2.14	--	1.67	1.70	1.65
91.4	151.1	2.90	--	2.47	--	1.95	2.02	2.17
93.7 (1)	151.1	3.62	3.09	2.92	2.61	2.46	2.37	1.94
108.2	151.1	5.80	5.02	4.90	4.31	4.84	4.40	3.91
123.5	151.1	4.82	4.35	4.17	--	4.22	3.72	3.24
138.7	151.1	3.32	2.87	2.82	2.58	2.90	2.58	2.33
154.0	151.1	2.01	1.79	1.73	1.57	1.80	1.66	1.58
169.2	151.1	1.07	0.89	0.91	0.86	0.88	0.85	0.83
184.4	151.1	0.30	0.27	0.27	0.24	0.12	0.14	0.24
0	0	0.16	0.20	0.17	0.16	0.18	--	0.20
0	13.9	1.20	1.36	1.25	1.14	1.30	--	1.25
0	29.1	2.58	2.77	2.58	2.17	2.56	--	2.46
0	44.4	4.21	4.26	4.02	3.50	4.21	2.46	3.86
0	59.6	5.78	5.75	5.39	--	5.71	3.82	5.54
0	74.9	6.21	5.76	5.60	4.66	5.75	4.53	5.58
0	89.4	2.85	1.64	2.07	1.80	1.66	1.66	2.04
0	90.1	2.58	1.38	2.33	2.14	1.52	1.44	1.80
0	105.3	--	0.78	--	--	--	0.70	--
0	121.5	2.31	0.66	1.19	--	0.86	0.84	1.00
0	135.8	--	0.75	--	1.48	--	--	0.96
0	151.1	2.30	0.69	1.11	--	0.80	0.73	0.94
0	166.3	--	--	--	1.38	--	--	--
0	181.5	2.29	--	1.12	1.30	0.82	0.86	1.01
0	196.8	--	0.80	--	--	1.02	1.21	--
0	212.0	2.60	1.25	1.71	2.04	1.63	1.37	1.66

(1) Distances for Configurations 4, 5 and 6 were 0.5 cm closer to the cavity wall in the D₂O

(2) All values for Configuration 3B are from indium foils. All other data are from gold foils.

Note: All flux values are $\times 10^6$ neutrons/cm²/ sec. and are for equivalent 2200 m/sec fluxes.

TABLE 3.10
Summary of Au Foil Cadmium Ratios

Location		Cadmium Ratio					
Radial (cm)	Axial (cm)	Configuration					
		1	2	3A	4	5	6
0	89.4	1.88	1.55	1.74	1.48	1.53	1.68
0	74.9	4.04	3.12	3.63	3.29	3.39	3.33
0	59.6	12.75	9.41	10.52	10.20	7.42	10.62
0	44.4	53.42	35.77	43.92	47.13	25.90	37.89
0	36.8	173.00	--	--	--	--	--
0	29.1	--	154.00	--	217.00	--	118.00
93.7 (1)	151.1	2.06	2.07	1.99	1.72	1.82	1.61
108.2	151.1	4.44	4.36	4.51	4.43	4.66	3.32
123.5	151.1	15.91	15.24	15.50	15.47	15.30	14.22
138.7	151.1	83.23	63.31	70.31	83.71	60.34	62.67
153.5	151.1	--	140.00	--	--	182.00	171.00
0	90.1	1.82	1.48	--	1.46	1.52	1.71
0	120.6	1.73	1.27	1.50	1.29	1.29	1.40
0	151.1	1.74	1.29	1.47	1.27	1.25	1.38
0	181.5	1.75	--	1.48	1.28	1.30	1.39
0	212.0	1.84	1.46	1.66	1.53	1.48	1.58
61.0	151.1	1.78	1.50 (2)	1.83	1.50	1.54	1.60
91.4	151.1	1.96	--	1.90	1.57	1.59	1.74
91.4	90.1	2.05	--	2.13	2.02	1.87	2.06
91.4	212.0	2.07	--	2.06	1.85	1.41	1.90

(1) On Configurations 4, 5 and 6 the radial distances reduced by 0.5 cm.

(2) Outer edge of the fuel, 43.8 cm from core center.

TABLE 3.11
Injector Tube and Exhaust Nozzle Power Measurements

Configuration	Ratio of Nozzle Power to Core Power
9 No poison	2.44×10^{-2}
9 0.0508 cm Cd around tube	1.21×10^{-3}
9 0.0254 cm Cd around tube	1.36×10^{-3}
9 0.152 cm borated stainless steel around tube	1.07×10^{-2}
10 No poison around nozzle	1.87×10^{-2}

Fig.3.1 Summary of configurations

Config. 4

Config. 5
Off Center

Config. 6

Config. 7A

Config. 7B

Config. 7C

Fig. 3.2 Summary of configurations

Fig. 3.3 Fuel radius effects on fuel mass and density

Fig. 3.4 Fuel worth vs. critical mass and fuel radius

Fig 3 5 Radial power distribution comparison at axial center of core - configurations 1, 2 and 3A

Fig. 3.6 Radial power distribution comparison at axial center of core - configurations 4, 5 and 6

Fig. 3.7 Axial power profile - configuration 7A

Fig. 3.8 Axial power profile - configuration 7C

Fig. 3.9 Axial power profile, configuration 7B

Fig. 3.10 Thermal neutron flux distribution radially through axial center of core - configuration 1

Fig. 3.11 Thermal neutron flux distribution axially through radial center of core - configuration 1

4.0 CONFIGURATION 1

4.1 Initial Loading

Initial loading of the first configuration of the Cavity Reactor began on March 21, 1966. The ratio of the fuel to cavity radius was 0.89 with a fuel radius of 81.4 cm. The 30.5 cm diameter end plug was in the reactor and only D₂O in the reflector. There were 494 surfaces on which fuel was placed as illustrated in Figure 4.1. Each tray was initially loaded with six fuel sheets per surface. The loading was varied from surface to surface as shown in Figure 4.2 and Table 4.1. This arrangement permitted a total loading of 2964 sheets of fuel, each sheet being 7.30 cm square by 0.00254 cm (one mil) thick.

The fuel was added to the reactor in several increments. By the 8th increment, 2849 sheets had been placed in the reactor and it was obvious that it would take considerably more than the predicted 2964 sheets to go critical. Based on the inverse multiplication curves, it was determined that it would take approximately nine sheets per surface, or about 4446 sheets, to produce a critical assembly. The initial fuel arrangement was not disturbed. The extra fuel was placed between the existing fuel sheets on each surface.

Three count rate channels were set up to record multiplication. The data recorded during the loading process are presented in Table 4.2 and are shown graphically in Figure 4.3. It will be noted that the reactor was critical on 4196 sheets of fuel in the reactor. The exact number of sheets and the total weight of fuel on each tray are given in Table 4.3. The total fuel loading amounted to 10,957.7 grams of Oralloy (93.2% enriched). The fuel was also weighed when the reactor was unloaded from an excess reactivity of 0.213%Δk. These weights summed to 11,006.4 grams with an average of 2.62 ± 0.069 gm per sheet. The fuel weights include some coating material (Fluorocarbon) and oxidized uranium. The coating represents nominally 0.1% of the total uranium weight or about 11 grams in the fully loaded core. The position of the control rods at the above critical level was all rods withdrawn except actuator No. 4 which was 25.6 cm withdrawn.

The required fuel loading for the initially loaded core was higher than originally calculated by about 3 kg. The layout of the fuel on the aluminum trays created a widely varying distribution of nuclear path lengths for neutrons in crossing the core. Some paths would encounter no fuel, other paths would encounter as many as 22 sheets at an incident angle of 30°. Unfortunately, selection of an orderly pattern to assure uniform dispersal did not preclude the alignment of sheets resulting in a "crystalline" type dispersion action on the neutron beam. A complete numerical analysis of the orientation of the various fuel sheets and the resultant statistical distribution of the path lengths was an impractical task. Instead, a normal distribution approximating a Gaussian was assumed.

Very little diffusion occurred in the cavity, and hence essentially all neutron paths were straight lines, whether or not they were terminated by absorption in fuel.

The probability of a neutron being absorbed in a gas filled cavity is easily calculated for a given path length through the gas (i.e., $1 - e^{-\Sigma t}$). If the gas were mocked up by discrete lumps of fuel (i.e., thin sheets), the probability of absorption in a given sheet of fuel is readily calculated as $1 - e^{-\Sigma t \sec \Theta}$, where Θ is the angle between the normal of the sheet (thickness t) and the neutron path. In the case of one sheet at the center of the cavity, the probability for absorption can vary from nearly zero to 1.0 for neutrons of perpendicular incidence compared to those of grazing incidence, respectively. Yet in a gaseous cavity, neutrons passing through the center all have nearly the same probability of absorption. The single-sheet effect, equivalent to what is normally called the self-shielding effect, amounts to about 6% and was observed on the small cavity insert test where, on the average, a neutron passed only through one sheet, but never more than about six.

When a neutron should encounter a relatively large average attenuation probability in crossing the cavity, and if the fuel arrangement is such that there is a large deviation about the average probability, then there is a distortion in the net average interaction probability. For instance, if a neutron encounters zero mean free paths of fuel, a second neutron encounters $1/2$ a mean free path, and the third a full mean free path, the average absorption probability is 0.342, less than the 0.394 expected if all three neutrons encounter one half of a mean free path. If the path lengths are all small and their variations are small, then the absorption probabilities ($1 - e^{-\Sigma t}$) can be approximated by Σt , and the average interaction rate is essentially equal to the interaction rate of the average path length. Again, this describes the situation for the small cavity insert, but is far from being the situation with the critical experiment cavity. In it, some neutron paths see no fuel (absorption probability 0.0) while others see as many as 22 sheets at an angle of incidence of about 30° (absorption probability of 97%).

A gaussian distribution of nuclear path lengths ($X = \Sigma t$) about the most probable value $\bar{X}$, with a variance σ , is:

$$\exp \left\{ -(X - \bar{X})^2 / 2\sigma^2 \right\}$$

where $\bar{X}$ = the most probable value, which is also the mean value if the distribution extends equally on both sides of $\bar{X}$.

The average value of the transmission factor is.

$$\overline{\exp(-X)} = \frac{\int_0^\infty \left[\exp(-X) \right] \left[\exp \frac{-(X - \bar{X})^2}{2\sigma^2} \right] dX}{\int_0^\infty \left[\exp \frac{-(X - \bar{X})^2}{2\sigma^2} \right] dX}$$

The solution to this equation can be shown to be:

$$\overline{\exp(-X)} = \left[\exp(-\bar{X}) \right] \left[\exp \frac{\sigma^2}{2} \right] \frac{\left(\begin{array}{l} \text{Area of E.F. from} \\ -\bar{X}/(\sigma - \frac{\bar{X}}{\sigma}) \text{ to } +\infty \end{array} \right)}{\left(\begin{array}{l} \text{Area of E.F. from} \\ -\bar{X}/\sigma \text{ to } +\infty \end{array} \right)}$$

where E.F. is the normal error function.

This expression, when considered by itself, does not show the relation between the most probable value of X , ($\bar{X}$), and the mean value of X , (X_{av}). Because of the constraint that X cannot assume negative values, the Gaussian distribution is chopped on one side, and $\bar{X}$ is always less than X_{av} , the relation being

$$X_{av} = \bar{X} + \frac{\frac{\sigma}{2\sqrt{\pi}} \exp\left[-\frac{\bar{X}^2}{2\sigma^2}\right]}{\text{Area of E. F. from } -\bar{X}/\sigma \text{ to } +\infty}$$

Figure 4.4 shows the relation between X_{av} and $\bar{X}$ for various values of σ . When a particular distribution of fuel sheets is inserted into a cavity, this is usually assumed to simulate a quantity of uranium gas of the same mass. Therefore, the average nuclear path length, $X = \Sigma t$, ideally should be the same in each case. A particular distribution of fuel sheets, approximated by a Gaussian chopped on one side (not allowing negative path lengths), can then be characterized by a most probable value $\bar{X}$ and a standard deviation σ , both of which must be compatible with the value of X_{av} . With the gaseous filled cavity, it is herein apriori assumed that the distribution of path lengths is nominally a symmetrical distribution, i.e., a Gaussian not chopped at either end, and that the average path length and the most probable path lengths are identical. Though, by the above postulate, the average nuclear path lengths are the same for both the sheet fuel and gaseous configurations in question, the nuclear interaction rate will be much larger on the one with the narrowest and most symmetrical distribution, i.e., the gaseous configuration.

For the initial cavity reactor configuration (No. 1), the mean nuclear chord length, $X = \Sigma t = \Sigma(S/4V)$, was 0.52, giving a corresponding "mean" transmission factor of 0.595. Assume, for a case of illustration, that this represents a gaseous configuration with a narrow distribution of path lengths, and will be used as a reference configuration. The following table lists three distributions about this reference $\bar{X}$, each giving rise to an X_{av} , and a corresponding average interaction rate. Finally, each $\bar{X}_{av}$ is interpreted as a new gaseous core with a narrow distribution, so that X_{av} and $\bar{X}$ correspond, and the gaseous core interaction rate is compared with the foil (maldistribution) interaction rate.

Reference Case: $\bar{X} = X_{av} = 0.52$

Variance (σ) of "Foil" Distribution	X_{av}	Average Interaction Factor (Foil)	Interaction Factor of X_{av} (Gas)	Interaction Ratio of Gas Core to "Foil" Core
0.25	0.532	0.395	0.4125	1.044
0.5	0.657	0.432	0.482	1.115
1.0	1.02	0.548	0.640	1.170
2.0	1.80	0.703	0.835	1.187

The ratio of interaction rates in the two cores is quite different from the ideal ratio of 1.0. Though the larger variance values in the table are not pertinent to the foil distribution used in Configuration 1, a variance (σ) of 0.25 for the distribution is not unlikely. Such a variance results in a Gaussian distribution with 1.9% of the area in the "forbidden" region, i.e., where the nuclear path lengths would be negative. This 1.9% could be re-interpreted as the fraction which see a zero path length. An even larger fraction might be appropriate for the fuel arrangement of Configuration 1. Thus, it is apparent that an interaction rate difference of as high as 10% is probable for Configuration 1 vs. a gaseous core with the same fuel mass. Such differences in interaction rates translate directly to differences in critical fuel loading.

For configurations with smaller radii and higher fuel densities, the most probable transmission probability approaches zero. In such cases, the spread of the representative Gaussian distribution is not a very sensitive factor on the interaction rate, until the spread is so large that a significant number of nuclear paths are of negative (truncated to zero) length. Therefore, the fuel distribution in subsequent configurations was modified by reducing the spacing between the trays, giving a geometry, for the heavy loadings, in which less than 1/2% of the total solid angle had free streaming paths, i.e., zero nuclear path length.

As an example of the distribution effects in a heavily loaded core, consider a fuel region with 29 kg of U^{235} in a 4 ft diameter. This has a nuclear path length, based on the mean chord length *, of 2.48.

Heavily Loaded Case: $\bar{X} = 2.48$

Variance (σ) of "Foil" Distribution	X_{av}	Average Interaction Factor (Foil)	Factor of X_{av} (Gas)	Interaction Ratio of Gas Core To "Foil" Core
0.25	2.48	0.913	0.916	1.003
0.50	2.48	1.905	0.916	1.013
1.0	2.67	0.872	0.931	1.067
2.0	2.90	0.841	0.945	1.122

The above table shows that significant differences in interaction rate occur only for much wider spread distribution (larger σ) than was the case for the reference, lightly loaded core.

It is worth noting that an experiment in which the cavity walls are lined with foils, as done by Bell (1), also has path length distribution problems. Zero nuclear path lengths through the fuel region are precluded, but the nuclear path length distribution is, in essence, the opposite of that occurring in a gaseous-fueled cavity. In the latter, paths through the center are the longest (nuclearly), those through the edge the shortest. The opposite is true in the case of the configuration in which foils line the cavity wall. It was decided that it was preferable to distribute the fuel throughout the cavity, and concentrate efforts on eliminating the zero path lengths, rather than accept the "reversal" of the gaseous distribution.

* Mean chord length calculated as $4V\sigma S$, V = volume, S = surface area.

Experiments were performed on the configuration with the larger fuel radii to evaluate the effect of fuel arrangement and fuel sheet orientation within the fueled volume, (See Section 4.2.2). Fuel was randomly re-arranged on trays, screens were placed directly on each other to increase the streaming void, and deliberate orientation of the fuel into large values of ΣX were made. It was estimated from these measurements that the optimum arrangement of fuel sheets would have increased the reactivity on this configuration approximately $3\% \Delta k$, which is nominally the same as the 10% increase in fuel loading estimated above. This estimate is based on the value $0.3\% \Delta k/k$ per $\Delta m/m$ measured for this configuration.

4.2 Rod Calibrations and Reactivity Measurements

4.2.1 Rod Calibrations

With 4146 sheets of fuel in the reactor and all rods withdrawn, the system was slightly subcritical. At this point in the initial loading, subcritical rod worth curves were measured for two rod configurations, all rods as a bank and actuator 4 by itself with the other rods in the withdrawn position. Six actuators of rods were used for control purpose during this phase of testing. Each actuator contained three poison rods except for actuator 4 which contained two rods. The layout of these rods is shown in Figure 2.5.

The rod worth curves were generated by observing and recording the counts from the three count rate channels at each rod position. The counts are then divided into count-rate-zero. The resulting inverse multiplication values were then corrected by the following expression:

$$CR_0/CR_{\text{corrected}} = \frac{CR_0/CR}{1-CR_0/CR}$$

The data were further ratioed to the total difference in inverse count rate between the two extremes of rod position (in and out) to obtain the rod worth curves as shown in Tables 4.4 and 4.5. The curves produced from these data are presented in Figure 4.5. There was very little difference between the two curves, as will be observed.

In order to consistently read the curves and obtain the maximum possible accuracy, a smooth differential curve was drawn from the rod worth curves. A table was then produced from the differential curves giving the percent worth inserted for each 100-digit increment and the total percent worth inserted in 100-digit increments over the complete rod travel. These data are presented in Tables 4.6 and 4.7. These tables were "spot-checked" several times during the experiment, particularly when substantial changes occurred in the configurations. No difference in control rod shape was detected.

After the reactor was fully loaded with fuel, actuator 4 was "bumped" three times to determine its worth. This actuator contained only 2 rods and the average worth was $-0.528 \pm 0.023\% \Delta k$. Additional rod worth measurements were considered unnecessary for operational purposes at this time since the estimated worth of all rods based on actuator 4 was at least twice that required for safe operation.

4.2.2 Material Worth Measurements

Shortly after the reactor was fully loaded, measurements were made to determine, if possible, any significant variation in fuel worth in the cavity which might be attributed to neutrons streaming through the spaces in the trays where there was no fuel and between fuel trays. Thirty-two fuel sheets, 85.3 grams, were taped to an aluminum plate which was 30.5 cm wide by 61 cm long and weighed 130 grams. The reactivity of this assembly was measured in several positions, the results of which are presented in Table 4.8. Power distribution data explain in part the difference between the values on the radial cavity wall and the center of the movable reflector tank. The fission flux was about 14% lower at the end of the core where the plate was placed than at the outer edge of the cavity near the separation plane. The three points on the radial wall of the cavity vary from the average by only $\pm 2\%$ which is within the measurement statistics. The higher worth of the fuel and aluminum near the center of the fuel (top of tray 10) can be explained in part by the worth of aluminum. Aluminum was measured on the top of and at the center of tray 9 to be worth $-4.14 \pm .07 \times 10^{-5} \% \Delta k / \text{gm}$. This gives a value for the worth of the 130 gm of Al in the center of the core of $-0.0054 \% \Delta k$. Measurements on the subsequent experiments gave a worth for the 130 gm of Al at the cavity surface of $-0.043 \% \Delta k$. Nevertheless, the "plate-fuel" worths are substantially less (after accounting for the aluminum) than the fuel-sheet worth measurements described below. Though differences were observed, these measurements did not lead to any definite conclusion concerning a pattern effect caused by streaming of neutrons.

The fuel on tray 14 was re-arranged so as to be on every other surface rather than dispersed over all 28 surfaces. This caused a measured increase in reactivity of $0.0135 \% \Delta k$. The re-arrangement of fuel on tray 14 reduced possible streaming paths where neutrons could pass through the tray without encountering a sheet of fuel. A linear extrapolation of this reactivity increase to the entire reactor yields an increase of $1.4 \% \Delta k$. Assuming fuel to be worth $2.8 \times 10^{-3} \% \Delta k / \text{gram}$, this reactivity increase represents 465 grams of fuel or 4.7% of the total fuel loading.

The fuel was reoriented on tray 13 as was done on tray 14 and an increase of $0.0145 \% \Delta k$ was measured. This is essentially the same values as for tray 14 within the experimental error of about $0.007 \% \Delta k$ per reactivity measurement.

Fuel worth measurements were obtained at several locations in the reactor and the data are given in Table 4.9. Except for the average worth of the fuel on tray 11, the results appear to be consistent. It will be noted that placing the fuel sheets at right angles to the trays did not alter the fuel worth significantly. The sheets of fuel were merely rotated within the channels of the trays to a position normal to the surfaces. From the center to the outer edge of the cavity at the separation plane, the fuel sheets at right angles to the trays show a 21% increase in fuel worth.

Fuel tray 10 was stacked on top of tray 11 to deliberately increase streaming paths for neutrons and lump the fuel. This cause k-excess to decrease $0.109 \pm 0.010\% \Delta k$. This was an extreme case, but substantiates the argument that fuel lumping can account, in part, for the heavier-than-predicted fuel loading. From these results, it can readily be deduced that the streaming paths which allow neutrons to pass through the reactor without encountering any fuel will account for 1.0 to 1.5% Δk . This represents from about 3.5 to 5% of the total fuel loading.

Thus, the sum of the effects of fuel lumping and (as discussed in the above paragraph) of streaming paths (as determined from ordered fuel re-arrangements) could, therefore, represent a penalty of as much as 3% Δk in reactivity, or 10% in fuel loading. These results are similar to the conclusions from the Gaussian path length distribution analysis.

4.2.3 Table Separation Worth Measurements

Mechanical and safety requirements dictated a separation distance between the movable and fixed tanks of at least 0.635 cm. The effect of table separation was measured over a small motion of the table as shown in Table 4.10.

In addition to the void at the separation plane, there was 2.54 cm of aluminum in the two ends of the tanks. To evaluate the aluminum worth, 0.081 cm thick sheet of Al was placed in the void over a 92 degree sector. It caused excess reactivity to decrease $0.0143 \pm 0.0100\% \Delta k$. The worth of placing this sheet all the way around the separation plane extrapolates to $-0.056 \pm 0.039\% \Delta k$ or $-0.689 \pm 0.480\% \Delta k$ per cm. This measurement was made with configuration 3A and is discussed in Section 6.2.2.

The worth of the 2.54 cm thick Al at the separation plane extrapolates to $-1.750 \pm 1.219\% \Delta k$. The 0.952 cm void gap was worth $-0.524 \pm 0.056\% \Delta k$. Therefore, the total worth of the gap and aluminum at the separation plane was $-2.274 \pm 1.221\% \Delta k$. The elimination of the aluminum and gap would reduce the fuel loading by about 8%.

4.3 Power Distribution Measurements

4.3.1 Bare Catcher Foils

Power distribution measurements over the fueled region of the reactor were obtained using standard catcher foil techniques. Foils were normally 1.429 cm diameter by 0.0254 cm thick aluminum. The aluminum foil was placed against a clean, bare Orallo (uranium) foil of the same diameter and the two foils were placed inside a 0.0254 cm thick aluminum bucket and cover assembly for exposure in the reactor. The catcher foils were somewhat sensitive to proper contact with the uranium foil and it was sometimes difficult to assure good contact after the foils were mounted in the buckets and covers. For this reason, there was some data scatter outside of the normally expected standard deviation of about $\pm 3.0\%$ (including counting statistics).

Normalizer catcher foils were mounted on the fixed reflector tank at the separation plane. Each power distribution run contained a set of normalizer foils which were used to normalize the power data. All bare catcher foil data were again normalized to the foil at the axial and radial center of the reactor. Foil exposures were made with all rods withdrawn except actuator 4 which was approximately 8 cm withdrawn and at an average D_2O temperature of $23^{\circ}C$.

All of the catcher foil data obtained on Configuration 1 are given in Table 4.11. These data are summarized in Figures 4.6 and 4.7. All axial locations of foils are referenced to the outside surface of the D_2O at the end of the cavity containing the control rods. Plots of axial distribution of power and flux data are similarly referenced unless specifically noted otherwise.

The radial power profile shows a 19% power decrease from the outer edge of the fuel to the center of the core. This radial profile flattens toward each end of the fueled region to about an 8% attenuation. The weighted average radial power distribution of 1.079 at the axial center of the core is a volume weighted average.

The axial power distribution shows a definite difference between the two ends of the cavity with the separation plane being consistently lower than the other end of the core. This is undoubtedly due to the gap between tables and the extra aluminum in the tanks at the separation plane. As can be seen from Figure 4.7, the power at the separation plane is 10% above the core center and the power at the other end of the core is 16% above the core center. At the outer edge of the reactor the axial power is considerably flatter than at the core center as would be expected. Essentially the same ratio of the power at the control rod end of the core to that at the separation plane was observed at the outer edge of the fuel as at the center of the core (1.06).

There was some concern that the power distribution might be different if the foils were placed about half way down the corrugated surfaces on which the fuel sheets were placed compared to placing them on top of the tray at the apex of each corrugation. A measurement was made, therefore, to determine the difference. The results are shown in Figure 4.8. There was 5% less power at the middle of the tray surfaces than on top of the tray. Since the primary interest was in relative power distribution, it made little difference whether the foils were placed on top of the tray or at some location on the fueled surfaces as long as all foils were consistently in one or the other position. All of the data were from foils placed on top of the trays.

The above data show that there was neutron streaming between the trays thus giving 5% higher fission flux in the one-inch gap between trays than would be found within the valleys of the trays.

4.5.2 Cadmium Ratios - Catcher Foils

The normalized counts from the cadmium covered catcher foils are also given in Table 4.11. Catcher foil cadmium ratios were

taken in the cavity only and 0.0508 cm thick cadmium covers were used in all cases. The resulting cadmium ratios are presented in Table 4.12. The ratio at the core center is about 22.2 and increases to approximately 24.5 at the radial center and ends of the cavity. The peak ratio of 30.4 occurs at the end of the cavity and at the outer radial position of the control rod end of the active core. The single set of data repeated at the same point shows a $\pm 1.7\%$ difference which is better than expected as the observed counts from the foils had a standard error as large as $\pm 2.0\%$. The average cadmium ratio shows that less than 4% of the fissions occur above the nominal cadmium cut off of 0.45 ev.

4.4 Resonance Detector Data - Gold Foils

Both bare and cadmium covered gold foils were exposed in the cavity region and in both the end and radial reflectors. A regular rod guide tube traversed the end reflector at the center of the cavity in the end of the reactor containing the control rods (reference end of the core). A water tight aluminum tube (1.905 cm O. D. by 1.588 cm I. D.) was inserted through the port at the top of the fixed tank so as to be at the axial center of the core. The gold foils were placed in these two tubes to measure the flux in the end and radial reflectors.

4.4.1 Bare Gold Foil Data

The gold foil data are given in Table 4.13, which contains both bare and cadmium covered results. The bare gold relative radial and axial activation distributions are shown in Figures 4.9 and 4.10. In all cases the radial and axial power variations are less than for catcher foils. The ratio of the center to core edge fluxes at the axial midplane is 1.17 compared to 1.25 for catcher foils. Likewise the same ratio at the reference end of the core at the radial center of the core is 1.09 for gold and 1.16 for catcher foils. As with catcher foils, the flux is lower at the separation plane than at the control rod end of the core. It should be noted from Table 4.13 that the gold data from Run 1002 were from 0.0127 cm thick foils. All other gold foils were 0.00127 cm or less in thickness. Run 1002 data were not used in the curves because of the inaccuracy of the resonance self-shielding correction.

The traverses through the reflectors are presented in Figure 4.11. The activation flux in the end reflector is consistently higher than in the radial reflector except at the inner and outer surfaces of the reflector. There is a peak occurring around 15 cm inside the D_2O . The data normally fall within 5% of the smooth curve which is approximately the standard error for gold disintegration rates determined with these very thin foils.

The gold foil data were power normalized as noted in Table 4.13. Power normalization foils were exposed for each foil exposure in the reactor. These were catcher foils and were positioned on the fixed tank at the separation plane. The catcher foils exposed within the cavity were automatically normalized to 100,000 counts on the normalizer foils. The gold foils, however, were counted on the 256 channel gamma ray analyzer and the absolute disintegration rate

determined from the activity under the 0.41 Mev photo peak. The gold foil data were power normalized by first reducing the power normalizer foils to counts per minute at 50 minutes after shutdown. Run 1002 was used as the reference run to which all of the gold data were normalized. The average count rate at 50 minutes after shutdown for the normalizers on this run was 79464 counts per minute. All of the gold foil data for this complete test series were power normalized to this reference run. The normalization factors for Configuration 1 are given in Table 4.14.

Since all of the catcher foil data were normalized to the core center, it was also desirable to reference the gold data to the same point on an absolute power basis. This is readily accomplished as follows:

1. Average catcher foil counts normalized to 100,000 counts on the normalizers was 103707 ± 1280 at the core center.
2. Normalizer count-per-minute at 50 minutes after shutdown was 79464 ± 58 .
3. For these small, scintillation-head beta counters, ⁽³⁾ there are 123.2 ± 8.6 fissions-per-second per gram of U-235 for each count-per-minute from a 1.429 cm diameter catcher foil exposed in the reactor for 20 minutes.
4. There are 3.2×10^{10} fissions-per-second per watt of power.
5. The specific power (per gram of U-235) at the core center with respect to Run 1002, the reference run, would be

$$\frac{103707 \times 79464 \times 123.2}{100000 \times 3.2 \times 10^{10}} = 3.17 \times 10^{-4} \text{ watts/gm U-235}$$

This value has an estimated total standard error of about 8%. The total reactor power for the reference run may then be calculated by factoring in the weighted radial average, the axial average and the total U-235 fuel in the reactor. This gives the following result:

$$3.17 \times 10^{-4} \times 1.079 \times 1.036 \times 11 \times 10^3 \times 0.932 = 3.63 \text{ watts}$$

This assumes a constant relative radial and axial power distribution throughout the core. While this assumption is not completely valid, a detailed integration of the power distribution over the core volume gave the same final answer. Detailed integrations required considerable interpolation and extrapolation of the available data as extensive three dimensional power mapping data was not obtained.

4.4.2 Cadmium Ratios - Gold Foils

Cadmium covered gold foil data are given in Table 4.13. The resulting cadmium ratios are presented in Table 4.15. The measured cadmium ratios were corrected for self-shielding to give values based on infinitely dilute foils by the method described in Section 4.4.3.

σ_o	=	Theoretical peak cross section of resonance
Γ_r	=	gamma width
Γ	=	total width ($\Gamma_r + \Gamma_n$)
I_∞	=	Infinitely dilute resonance integral
I_{eff}	=	Effective resonance integral
S	=	Foil surface area
V	=	Foil volume

The sub-cadmium foil activity was determined as follows:

$$SA = C - A / \frac{I_\infty}{I_{\text{eff}} (\text{bare foil})}$$

where:

SA	=	Subcadmium foil activity in d/s-gm at shutdown
C	=	Bare foil activity in d/s-gm at shutdown
A, I_∞ and I_{eff}	=	are as defined for the previous equation

This expression reduces to the following equation:

$$SA = C - A \sqrt{\frac{\pi R^2}{\pi R^2 + 2 N W \sigma_o \left(\frac{\Gamma_r}{\Gamma} \right)}}$$

where the expression under the square root sign is for the bare foil.

The thermal neutron flux was then calculated from the following:

$$SA = \Sigma a \Phi V (1 - e^{-\lambda t})$$

where:

Σa	=	Macroscopic absorption cross section
Φ	=	Neutron flux
V	=	Volume of 1 gram foil weight
λ	=	Decay constant
t	=	Foil exposure time in reactor

The effective resonance integrals were calculated from the resonance parameters by the method given by Kelber ⁽⁴⁾. These corrected (infinitely dilute) cadmium ratios are given in Table 4.15. Within the active core, the cadmium ratio is about 1.80 and increases to about 2.00 at the core edge and to about 2.07 at the corners of the cavity.

The cadmium ratios in the reflector are given graphically in Figure 4.12. Within the experimental error, the radial and end reflector are the same. The errors noted in Figure 4.12 are due only to counting errors. Where the error was 5% or less no indicated variance was shown in the figure. The large error as the distance in the reflector increases was due entirely to the very low counting rates on the cadmium covered gold. Beyond about 50 cm from the cavity wall, it was impractical to obtain cadmium covered gold data.

4.4.3 Thermal Neutron Flux Distribution - Gold Foils

The bare and cadmium covered gold foil data were used to calculate thermal neutron flux in the cavity and radial reflectors. The cadmium covered foil activity in disintegrations per second per gram of foil material was first corrected to infinitely dilute activity by a single level resonance formula as follows: *

$$A = B \frac{I_{\infty}}{I_{\text{eff}}} \quad \text{where} \quad \frac{I_{\infty}}{I_{\text{eff}}} = \frac{1}{\sqrt{\frac{S/4NV}{S/4NV + \sigma_0} \left(\frac{f}{f} \right)}}$$

This reduced to

$$A = B / \sqrt{\frac{\pi R^2 \rho}{\pi R^2 \rho + 2NW \sigma_0} \left(\frac{f}{f} \right)}$$

where:

A	=	Infinitely dilute cadmium foil activity in d/s-gm at shutdown
B	=	Uncorrected cadmium covered foil activity in d/s-gm at shutdown
R ²	=	Foil radius in cm
ρ	=	Foil density in grams/cm ³
N	=	Number of absorbing atoms/cm ³
W	=	Cadmium covered foil weight

* For both gold used indium, the principal low energy resonance accounts for over 90% of the resonance integral.

The results of these calculations were normalized to one watt of reactor power and plotted to show the neutron flux distribution in the radial and axial directions through the cavity and reflectors as shown in Figures 4.13 and 4.14. The listed results are given in Table 4.15.

Beyond about 60 cm in the reflector regions no cadmium covered foil data were obtained, as the foil activation was too low to accurately count. In order to calculate the flux levels out to the edge of the reflector, extrapolated values were used. Since the epi-cadmium component was very small, little or no error was induced from using the extrapolated values.

Gold foils ranged in thickness from 0.000508 to 0.00127 cm and were all 1.429 cm in diameter. Because the foils were very thin, thermal flux perturbation was negligible (1% or less) and was, therefore, not considered in the calculations.

Considering all possible errors associated with the foils and the calculations to obtain thermal flux, the expected standard error on the results at any given location is about 10%.

TABLE 4.1
Fuel Tray Loading - Configuration 1

	Tray No. and Type Loading																							
Surface No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	No. Fuel Sheets	
1	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	132	
2	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	132	
3	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	132	
4	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	132	
5	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	132	
6	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	132	
7	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	132	
8	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	132	
9		2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	126	
10		3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	126	
11		4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3		120	
12		1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4		120	
13		2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1		120	
14		3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2		120	
15		4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3		120	
16			2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4		114	
17			3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4			108	
18			4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1			108	
19			1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1				102	
20				3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2				96	
21					1	2	3	4	1	2	3	4	1	2	3	4	1	2	3				90	
22					2	3	4	1	2	3	4	1	2	3	4	1	2	3	4				90	
23						4	1	2	3	4	1	2	3	4	1	2	3	4					78	
24						1	2	3	4	1	2	3	4	1	2	3	4	1					78	
25							3	4	1	2	3	4	1	2	3	4							60	
26							4	1	2	3	4	1	2	3	4	1							60	
27									3	4	1	2	3	4									36	
28									4	1	2	3	4	1									36	
																							Total	2964

TABLE 4.2
Inverse Multiplication - Configuration 1

Increment	Total Fuel (sheets)	Channel 1		Channel 2		Channel 3		Avg.	Rod Positions
		CPM	CRo/CR	CPM	CRo/CR	CPM	CRo/CR		
0	0	645		1051		688			In
0	0	658		1081		705			Out
1	444	750	.860	1174	.895	791	.870	.875	In
1	444	786	.837	1256	.861	835	.844	.847	Out
2	876	914	.706	1464	.718	972	.708	.711	In
2	876	988	.666	1577	.685	1054	.669	.673	Out
3	1320	1132	.570	1790	.587	1172	.587	.581	In
3	1320	1225	.537	1990	.543	1296	.544	.541	Out
4	1746	1390	.464	2242	.469	1453	.474	.469	In
4	1746	1535	.428	2443	.442	1615	.437	.436	Out
5	2034	1592	.405	2572	.409	1677	.410	.408	In
5	2034	1871	.352	2917	.371	1948	.362	.362	Out
6	2310	1898	.340	2941	.357	1934	.356	.351	In
6	2310	2255	.292	3511	.308	2313	.305	.302	Out
7	2568	2174	.297	3382	.312	2207	.312	.307	In
7	2568	2815	.234	4219	.256	2783	.253	.248	Out
8	2849	2599	.248	4022	.261	2608	.264	.258	In
8	2849	3454	.191	5329	.203	3430	.206	.200	Out
9	3147	3200	.202	4918	.214	3210	.214	.210	In
9	3147	4583	.144	6994	.155	4580	.154	.151	Out
10	3513	4273	.151	6662	.162	4325	.159	.157	In
10	3513	7350	.090	11,333	.095	7435	.095	.093	Out
11	3885	6356	.101	9750	.108	6413	.107	.105	In
11	3885	17,303	.038	26,230	.041	17,197	.041	.040	Out
12	4146	9326	.069	14,274	.074	9323	.074	.072	In
12	4146	144,696	.005	204,623	.005	138,701	.005	.005	Out
13	4196	11,374	.057	15,758	.067	101,163	.068	.064	In

TABLE 4.3

Fuel Loading at Criticality - Configuration 1

<u>Increment</u>	<u>Tray No.</u>	<u>No. Fuel Sheets</u>	<u>Total Weight (gm)</u>
3	1	48	128.2
7	2	90	235.5
9	2	21	52.9
4	3	114	288.9
12	3	57	148.8
1	4	120	318.8
10	4	60	151.2
5	5	132	341.3
10	5	66	166.3
6	6	144	373.3
11	6	72	187.2
2	7	156	445.5
11	7	78	202.8
3	8	156	407.5
9	8	36	90.7
9	9	168	437.1
9	9	39	98.3
1	10	168	441.0
10	10	84	211.7
8	11	168	439.7
9	11	39	101.4
4	12	168	435.5
12	12	84	219.2
2	13	168	454.4
11	13	84	218.4
7	14	168	438.2
11	14	84	218.4
1	15	156	414.9
10	15	78	196.6
5	16	156	407.5
10	16	78	196.6
3	17	144	377.7
9	17	34	85.7
4	18	144	377.0
12	18	72	187.9
6	19	132	341.5
13	19	50	130.0
2	20	108	280.7
11	20	54	140.4
3	21	96	248.7
12	21	48	125.3
8	22	60	157.6
9	22	14	36.4
TOTALS		4196	10,956.7 gm

T A 1.4

Subcritical Rod Shape Data - All Rods

CHANNEL 1

<u>Ratiometer Reading</u>	<u>CPM</u>	<u>CRo/CR</u>	<u>Corrected CPO/CR</u>	<u>Relative Worth Withdrawn</u>	<u>Percent Worth Withdrawn</u>
In (105)	10459	.06224	.06637	0	0
1000	14062	.04628	.04853	0.01784	28.66
2000	19914	.03269	.03380	0.03257	52.32
3000	29055	.02241	.02292	0.04345	69.80
4000	44260	.01471	.01493	0.05144	82.63
5000	62134	.01048	.01059	0.05578	89.60
6000	87098	.00747	.00753	0.05884	94.52
7000	121048	.00538	.00541	0.06096	97.93
8000	145256	.00448	.00450	0.06187	99.39
9000	158127	.00411	.00413	0.06224	99.98
9804(out)	158647	.00410	.00412	0.06225	100.00

CHANNEL 2

In (105)	14474	.07365	.07951	0	0
1000	19118	.05576	.05905	0.02046	27.53
2000	27191	.03920	.04080	0.03871	52.08
3000	39480	.02700	.02775	0.05176	69.64
4000	58880	.01810	.01843	0.06108	82.17
5000	83286	.01280	.01296	0.06655	89.53
6000	116943	.00912	.00920	0.07031	94.59
7000	157855	.00675	.00680	0.07271	97.82
8000	189028	.00564	.00567	0.07384	99.34
9000	205414	.00519	.00522	0.07429	99.95
9804(out)	206928	.00515	.00518	0.07433	100.00

CHANNEL 3

In (105)	9176	.07600	.08225	0	0
1000	12324	.05656	.05995	0.02230	28.89
2000	17592	.03962	.04125	0.04100	53.12
3000	25920	.02689	.02763	0.05462	70.77
4000	38432	.01814	.01947	0.06377	82.62
5000	54365	.01282	.01298	0.06926	89.73
6000	76465	.00912	.00920	0.07305	94.64
7000	105088	.00663	.00667	0.07558	97.92
8000	126312	.00552	.00555	0.07670	99.37
9000	137269	.00508	.00510	0.07714	99.94
9804 (out)	138404	.00504	.00506	0.07718	100.00

AVERAGE OF 3 CHANNELS

In (105)	.07604	0	0
1000	.05584	0.02020	28.35
2000	.03862	0.03742	52.52
3000	.02610	0.04994	70.09
4000	.01728	0.05876	82.47
5000	.01218	0.06386	89.63
6000	.00864	0.06840	96.00
7000	.00629	0.06975	97.89
8000	.00524	0.07080	99.37
9000	.00482	0.07122	99.96
9804 (out)	.00479	0.07125	100.00

TABLE 4.5

Subcritical Rod Shape Data - Actuator 4

CHANNEL 1					
Ratiometer Reading	CPM	CRo/CR	Corrected CRo/CR	Relative Worth Withdrawn	Percent Worth Withdrawn
In (115)	54631	.01204	.01218	0	0
1000	65342	.01007	.01017	201	25.22
2000	81745	.00804	.00811	407	51.07
3000	99866	.00658	.00662	556	69.76
4000	117709	.00559	.00562	656	82.31
5000	132600	.00496	.00498	720	90.34
6000	144904	.00454	.00456	762	95.61
7000	151670	.00433	.00435	783	98.24
8000	156204	.00421	.00423	795	99.75
9000	157199	.00418	.00420	798	100.12
9817 (out)	156951	.00419	.00421	797	100.00
CHANNEL 2					
In (115)	74058	.01459	.01481	0	0
1000	89018	.01214	.01229	252	26.28
2000	111018	.00973	.00982	499	52.03
3000	133608	.00809	.00816	665	69.34
4000	155934	.00693	.00698	783	81.65
5000	176251	.00613	.00617	864	90.09
6000	192204	.00562	.00565	916	95.52
7000	201073	.00537	.00540	941	98.12
8000	207158	.00521	.00524	957	99.79
9000	208204	.00519	.00522	959	100.00
9817 (out)	208049	.00519	.00522	959	100.00
CHANNEL 3					
In (115)	48368	.01457	.01478	0	0
1000	57752	.01220	.01235	243	25.00
2000	72473	.00972	.00982	496	51.03
3000	88114	.00800	.00806	672	69.14
4000	102762	.00686	.00691	787	80.97
5000	117199	.00601	.00605	873	89.81
6000	127553	.00552	.00555	923	94.96
7000	135283	.00521	.00524	954	98.15
8000	138171	.00510	.00513	965	99.28
9000	139066	.00506	.00508	970	99.79
9817 (out)	139903	.00503	.00506	972	100.00
AVERAGE OF 3 CHANNELS					
In (115)	Avg. all Rods (105)	.01392	0	0	
1000		.01160	232	25.52	
2000		.00925	467	51.38	
3000		.00761	631	69.42	
4000		.00650	742	81.63	
5000		.00573	819	90.10	
6000		.00525	867	95.38	
7000		.00500	892	98.13	
8000		.00487	905	99.56	
9000		.00483	909	100.00	
9817 (out)	(9804)	.00483	909	100.00	

TABLE 4.6

Tabular Rod Worth - Actuator No. 4

Ratiometer
Reading

Percent Inserted

	0	100	200	300	400	500	600	700	800	900
0	100.00	100.00	97.14	94.30	91.46	88.64	85.83	83.02	80.23	77.46
1000	74.72	72.00	69.29	66.61	63.94	61.32	58.72	56.15	53.63	51.16
2000	48.79	46.52	44.39	42.36	40.44	38.61	36.88	35.23	33.64	32.12
3000	30.65	29.23	27.87	26.55	25.27	24.04	22.84	21.69	20.57	19.50
4000	18.46	17.47	16.51	15.59	14.71	13.86	13.05	12.27	11.53	10.82
5000	10.14	9.50	8.88	8.29	7.73	7.21	6.71	6.23	5.77	5.34
6000	4.93	4.55	4.19	3.85	3.53	3.24	2.96	2.69	2.45	2.22
7000	2.01	1.81	1.63	1.47	1.32	1.18	1.05	.93	.82	.72
8000	.62	.54	.45	.37	.30	.24	.19	.15	.11	.08
9000	.06	.04	.02	00	00	00	00			

Difference Table

	0	100	200	300	400	500	600	700	800	900
0	0	0	2.86	2.84	2.84	2.82	2.81	2.81	2.79	2.77
1000	2.74	2.76	2.71	2.68	2.67	2.62	2.60	2.57	2.52	2.47
2000	2.37	2.27	2.13	2.03	1.92	1.83	1.73	1.65	1.59	1.52
3000	1.47	1.42	1.36	1.32	1.28	1.23	1.20	1.15	1.12	1.07
4000	1.04	.99	.96	.92	.88	.85	.81	.78	.74	.71
5000	.68	.64	.62	.59	.56	.52	.50	.48	.46	.43
6000	.41	.38	.36	.34	.32	.29	.28	.27	.24	.23
7000	.21	.20	.18	.16	.15	.14	.13	.12	.11	.10
8000	.10	.08	.09	.08	.07	.06	.05	.04	.04	.03
9000	.02	.02	.02	.00	.00					

TABLE 1.

Tabular Rod Worth All Rods

Ratiometer
Reading

Percent inserted

	0	100	200	300	400	500	600	700	800	900
0	100.00	100.00	96.54	93.16	89.86	86.64	83.50	80.43	77.74	74.52
1000	71.68	68.92	66.23	63.62	61.08	58.61	56.22	53.90	51.64	49.45
2000	47.34	45.29	43.30	41.38	39.52	37.72	35.99	34.32	32.71	31.16
3000	29.66	28.21	26.82	25.48	24.19	22.95	21.77	20.63	19.53	18.48
4000	17.48	16.52	15.60	14.72	13.88	13.08	12.32	11.59	10.89	10.23
5000	9.59	8.99	8.42	7.87	7.34	6.85	6.38	5.93	5.50	5.10
6000	4.72	4.35	4.01	3.68	3.38	3.08	2.81	2.55	2.30	2.08
7000	1.86	1.66	1.47	1.30	1.14	.99	.85	.73	.62	.52
8000	.43	.35	.28	.22	.18	.14	.11	.09	.08	.08

Difference Table

	0	100	200	300	400	500	600	700	800	900
0	0	0	3.46	3.38	3.30	3.22	3.14	3.07	2.99	2.92
1000	2.84	2.76	2.69	2.61	2.54	2.47	2.39	2.32	2.26	2.19
2000	2.11	2.05	1.99	1.92	1.86	1.80	1.73	1.67	1.61	1.55
3000	1.50	1.45	1.39	1.34	1.27	1.24	1.18	1.14	1.10	1.05
4000	1.00	.96	.92	.88	.84	.80	.76	.73	.70	.66
5000	.64	.60	.57	.55	.53	.49	.47	.45	.43	.40
6000	.38	.37	.34	.33	.30	.30	.27	.26	.25	.22
7000	.22	.20	.19	.17	.16	.15	.14	.12	.11	.10
8000	.09	.08	.07	.06	.04	.04	.03	.02	.01	.00

TABLE 4.8

Reactivity Measurements - Configuration 1

Material	Location	Reactivity Change ($\% \Delta k$)
85.3 gm fuel attached to 130 gm Al sheet, 61 cm by 30.5 cm	Center of Cavity on surface of movable table	0.1052
Same as above	Cavity wall at bottom of cavity lined up with separation plane	0.1287
Same as above	Cavity wall at bottom and axial center	0.1250
Same as above	Cavity wall 90° from bottom at axial center	0.1298
Same as above	On top of and at center of Tray 10	0.1784
	Tray 10 stacked on top of Tray 11	-0.1090

The worth of the aluminum near the outer fuel boundary was measured in subsequent configurations to be -0.043 $\% \Delta k$ for the 130 gms.

TABLE 4.9
Fuel Worth - Configuration 1

<u>Location</u>	<u>Fuel Worth - $\% \Delta k / \text{gm}$</u>
Axial center -	$3.43 \pm 0.09 \times 10^{-3}$
Axial center - inner	$2.56 \pm 0.07 \times 10^{-3}$
Separation plane - outer radius	$3.77 \pm 0.19 \times 10^{-3}$
Separation plane - inner radius	$2.87 \pm 0.19 \times 10^{-3}$
Separation plane - inner radius at right angles to trays	$2.99 \pm 0.19 \times 10^{-3}$
Separation plane - outer radius at right angles to trays	$3.63 \pm 0.19 \times 10^{-3}$
Average worth of fuel on tray 11	$1.98 \pm 0.03 \times 10^{-3}$

TABLE 4.10
Reactivity Effect of Table Separation Near Closed Position - Configuration 1

<u>Table Motion⁽¹⁾ (cm)</u>	<u>Total Reactivity Change ($\% \Delta k$)</u>	<u>$\% \Delta k / \text{cm}$</u>
0.0173	-0.0126 ± 0.0100	0.728 ± 0.578
0.0330	-0.0169 ± 0.0100	0.512 ± 0.303
0.1008	-0.0553 ± 0.0100	0.549 ± 0.099
	Weighted Average ⁽³⁾	0.550 ± 0.059

(1) Separation motion from the normal closed position.

(2) Standard error assumed to be $0.007\% \Delta k$ per period measurement.

(3) Weighted by the standard error associated with each number.

TABLE 4.11
Catcher Foil Data - Configuration 1

Run 1002

Foil No.	Type	Location		Tray No.	Normalized Counts (1)	Ratio of Local to Core Center (Foil No. X)
		Radial (cm)	Axial (cm)			
1	Bare	0	212.6	11	111409	1.085
2	Bare	0	181.5	11	104875	1.022
3	Bare	0	151.1	11	102635	1.000 (X)
4	Bare	0	90.1	11	157751	1.537 (2)
5	Bare	30.5	151.1	11	104584	1.019
6	Bare	61.0	151.1	11	111792	1.089
7	Bare	91.4	151.1	11	128579	1.253
8	Bare	45.7	212.0	18	118182	1.151
9	Bare	45.7	196.8	18	111438	1.086
10	Bare	45.7	181.6	18	108343	1.056
11	Bare	45.7	166.3	18	107733	1.050
12	Bare	45.7	151.1	18	107687	1.049
13	Bare	45.7	135.8	18	108749	1.060
14	Bare	45.7	120.6	18	112756	1.099
15	Bare	45.7	105.3	18	115328	1.124
16	Bare	45.7	90.1	18	121204	1.181
17	Bare	91.4	212.0	12	128704	1.254
18	Bare	76.2	212.0	12	126613	1.234
19	Bare	61.0	212.0	12	120529	1.174
20	Bare	45.7	212.0	12	118231	1.152
21	Bare	30.5	212.0	12	117884	1.149
22	Bare	15.2	212.0	12	113856	1.109
23	Bare	7.6	212.0	13	114274	1.113
24	Bare	15.2	212.0	14	116193	1.132
25	Bare	22.9	212.0	15	115688	1.127
26	Bare	30.5	212.0	16	114985	1.120
27	Bare	38.1	212.0	17	116598	1.136
28	Bare	53.3	212.0	19	119653	1.166
29	Bare	68.6	212.0	21	125753	1.225
30	Bare	76.2	212.0	22	124424	1.212

TABLE 4.11
(Continued)

Run 1003

Foil No.	Type	Location		Tray No.	Normalized Counts	Ratio of Local to Core Center (Foil No. X)
		Radial (cm)	Axial (cm)			
1	Bare	15.2	212.0	14	113366	1.074
2	Bare	15.2	196.8	14	102584	0.971
3	Bare	15.2	181.6	14	103659	0.982
4	Bare	15.2	166.3	14	101727	0.963
5	Bare	15.2	151.1	14	102230	0.968
6	Bare	15.2	135.8	14	104128	0.986
7	Bare	15.2	120.6	14	107109	1.014
8	Bare	15.2	105.3	14	109364	1.036
9	Bare	15.2	90.1	14	120265	1.139
10	Bare	46.3	212.0	14	120585	1.142
11	Bare	46.3	196.8	14	107414	1.017
12	Bare	46.3	181.6	14	106851	1.012
13	Bare	46.3	166.3	14	103943	0.984
14	Bare	46.3	151.1	14	103425	0.979
15	Bare	46.3	135.8	14	104778	0.992
16	Bare	46.3	120.6	14	103701	0.982
17	Bare	46.3	105.3	14	112690	1.067
18	Bare	46.3	90.1	14	102505	1.141
19	Bare	85.1	212.0	14	117518	1.113
20	Bare	85.1	196.8	14	122406	1.159
21	Bare	85.1	181.6	14	112807	1.068
22	Bare	85.1	166.3	14	123256	1.167
23	Bare	85.1	151.1	14	123586	1.170
24	Bare	85.1	135.8	14	115805	1.097
25	Bare	85.1	120.6	14	126387	1.197
26	Bare	85.1	105.3	14	126955	1.202
27	Bare	85.1	90.1	14	127950	1.212
28	Bare	15.2	151.1	12	105529	1.000 (X)
29	Bare	30.5	151.1	12	105548	1.000
30	Bare	61.0	151.1	12	107939	1.022
31	Bare	76.2	151.1	12	118999	1.127
1	Cd	0	151.1	12	4649	
2	Cd	0	151.1	12	4575	
3	Cd	45.7	151.1	12	4742	
4	Cd	45.7	151.1	12	4765	
5	Cd	91.4	151.1	12	4935	
6	Cd	91.4	151.1	12	4905	

TABLE 4.11
(Continued)

Run 1004

Foil No.	Type	Location		Tray No.	Normalized Counts	Ratio of Local to Core Center (Foil No. X)
		Radial (cm)	Axial (cm)			
1	Bare	3.8	151.1	12	99385	0.964
2	Bare	12.4	151.1	12	103351	1.003
3	Bare	25.4	151.1	12	108165	1.050
4	Bare	27.9	151.1	12	99709	0.968
5	Bare	37.5	151.1	12	106319	1.032
6	Bare	49.5	151.1	12	107627	1.044
7	Bare	53.3	151.1	12	101459	0.984
8	Bare	62.2	151.1	12	108636	1.054
9	Bare	74.9	151.1	12	117982	1.145
10	Bare	79.4	151.1	12	112676	1.093
11	Cd	0	212.0	12	4898	--
12	Bare	0	20.19	12	108947	1.057
13	Bare	0	191.7	12	106023	1.029
14	Cd	0	181.5	12	4612	--
15	Bare	0	171.4	12	105308	1.022
16	Bare	0	161.2	12	102067	0.990
17	Bare	0	151.1	12	103052	1.000 (X)
18	Bare	0	140.9	12	104954	1.018
19	Bare	0	130.7	12	103674	1.006
20	Bare	0	120.6	12	105991	1.028
21	Bare	0	110.4	12	104579	1.015
22	Bare	0	100.3	12	112666	1.093
23	Bare	0	90.1	12	119572	1.160

Run 1005

1	Bare	0	212.0	12	117720	1.136
2	Bare	0	201.9	12	110411	1.066
3	Bare	0	191.7	12	101360	0.978
4	Bare	0	181.5	12	105455	1.018
5	Bare	0	171.4	12	105466	1.018
6	Bare	0	161.2	12	101973	0.984
7	Bare	0	151.1	12	103612	1.000 (X)
8	Bare	0	140.9	12	103986	1.004
9	Bare	0	130.7	12	105506	1.018
10	Cd	0	120.6	12	4571	--
11	Bare	0	110.4	12	106887	1.032
12	Bare	0	100.3	12	115228	1.112
13	Cd	0	90.1	12	4768	--

TABLE 4.11
(Continued)

Run 1005 (Cont'd)

Foil No.	Type	Location		Tray No.	Normalized Counts	Ratio of Local to Core Center (Foil No. X)
		Radial (cm)	Axial (cm)			
14	Bare	91.4	151.1	12	131996	1.274
15	Bare	76.2	151.1	12	122257	1.180
16	Bare	61.0	151.1	12	114996	1.110
17	Bare	45.7	151.1	12	107984	1.042
18	Bare	30.5	151.1	12	105144	1.015
19	Bare	15.2	151.1	12	106569	1.028
20	Cd	91.4	151.1	12	4839	--

Run 1009

1	Bare	91.4	212.0	12	128125
2	Bare	91.4	90.1	12	133645
3	Cd	91.4	212.0	12	4281
4	Cd	91.4	90.1	12	4399

- (1) Normalized to 100,000 counts on decay corrector.
 (2) Foil may have extended into end reflector slightly.

TABLE 4.12
Catcher Foil Cadmium Ratios - Configuration 1

Run No.	Location		Tray No.	Normalized Bare Foil Activity	Normalized Cd Foil Activity	Cd Ratio Bare/Cd Activity
	Radial (cm)	Axial (cm)				
1003,1004	0	151.1	12	103052	4612	22.3
1003,1005	45.7	151.1	12	107984	4754	22.7
1003,1005	91.4	151.1	12	131996	4920	26.8
1005,1005	91.4	151.1	12	131996	4839	27.3
1004,1005	0	212.0	12	117720	4898	24.0
1004,1005	0	181.5	12	105455	4612	22.9
1004,1005	0	120.6	12	105991	4571	23.2
1004,1005	0	90.1	12	119572	4768	25.1
1009	91.4	90.1	12	133645	4399	30.4
1009	91.4	212.0	12	128125	4281	29.9

TABLE 4.13

Gold Foil Data - Configuration 1

Run 1002

Foil No.	Type	Location		Activity (CPM) (1)	Foil Wt. (gm)	Specific Activity d/m/gm $\times 10^{-5}$ (2)
		Radial (cm)	Axial (cm)			
1	Bare	0.0	151.1	3490	.4088	1.442
2	Bare	15.2	151.1	3483	.4024	1.462
3	Bare	45.7	151.1	3589	.3950	1.535
4	Bare	61.0	151.1	3747	.3906	1.620
5	Bare	91.4	151.1	4098	.4046	1.711
6	Bare	0.0	135.8	3338	.3880	1.453
7	Bare	0.0	120.6	4139	.4168	1.677
8	Bare	0.0	105.3	3588	.4056	1.494

Run 1003

1	Bare	97.3	151.1	2736	.0348	12.416
2	Bare	111.9	151.1	3156	.0331	15.057
3	Bare	127.1	151.1	2728	.0385	11.190
4	Bare	142.3	151.1	1395	.0302	7.295
5	Bare	157.6	151.1	1132	.0399	4.480
6	Bare	172.8	151.1	564	.0385	2.313
7	Bare	188.1	151.1	104	.0273	0.602
8	Bare	0.0	89.4	2059	.0348	9.344
9	Bare	0.0	74.9	4117	.0416	15.629
10	Bare	0.0	59.6	3052	.0335	14.387
11	Bare	0.0	44.4	2361	.0376	9.916
12	Bare	0.0	29.1	1381	.0384	5.679
13	Bare	0.0	13.9	627	.0408	2.427
14	Bare	0.0	0.0	91	.0415	0.346

Run 1004

1	Cd	0.0	89.4	758	.0369	3.182
2	Bare	0.0	74.9	3619	.0338	16.583
3	Bare	0.0	59.6	2802	.0318	13.647
4	Cd	0.0	44.4	20	.0409	0.076
5	Bare	0.0	29.1	1437	.0348	6.396
6	Bare	0.0	13.9	728	.0357	3.158
7	Cd	0.0	0.0	1	.0418	0.004
8	Bare	93.7	151.1	3086	.0410	11.658
9	Bare	108.2	151.1	2793	.0282	15.340
10	Bare	123.5	151.1	2734	.0325	11.599
11	Bare	138.7	151.1	1705	.0339	7.790
12	Bare	154.0	151.1	1170	.0385	4.707
13	Bare	169.2	151.1	650	.0402	2.504
14	Bare	184.4	151.1	189	.0414	0.707

TABLE 4.13
(Continued)

No.	Foil Type	Location		Activity (CPM)	Foil Wt. (gm)	Specific Activity	
		Radial (cm)	Axial (cm)			d/ m/ gm $\times 10^{-5}$	(2)
Run 1005							
1	Bare	0.0	212.0	2374	.0431	8.913	
2	Bare	0.0	196.8	2173	.0421	8.352	
3	Bare	0.0	181.5	1631	.0308	8.568	
4	Bare	0.0	166.3	1739	.0341	8.252	
5	Bare	0.0	151.1	2023	.0391	8.372	
6	Bare	0.0	135.8	1889	.0380	8.044	
7	Bare	0.0	120.6	2111	.0406	8.413	
8	Bare	0.0	105.3	2025	.0379	8.645	
9	Bare	0.0	90.1	2038	.0361	9.135	
10	Bare	0.0	89.4	2279	.0376	9.807	
11	Bare	0.0	82.5	3375	.0367	14.880	
12	Bare	0.0	67.2	4191	.0425	15.956	
13	Bare	0.0	52.0	2745	.0368	12.069	
14	Bare	0.0	36.8	2079	.0399	8.431	
15	Bare	0.0	21.5	1031	.0338	4.936	
16	Bare	0.0	6.3	391	.0356	1.777	
17	Bare	15.2	151.1	1722	.0333	8.367	
18	Bare	30.5	151.1	1899	.0360	8.535	
19	Bare	45.7	151.1	1797	.0325	8.947	
20	Bare	61.0	151.1	1675	.0302	8.974	
21	Bare	76.2	151.1	1891	.0328	9.328	
22	Bare	91.4	151.1	2173	.0360	9.767	
23	Cd	93.7	151.1	884	.0475	3.011	
24	Bare	110.0	151.1	3309	.0388	13.799	
25	Bare	130.2	151.1	1824	.0307	9.614	
26	Bare	145.5	151.1	1800	.0483	6.030	
27	Bare	160.7	151.1	721	.0354	3.296	
28	Cd	182.8	151.1	0	.0358	0	
Run 1006							
1	Cd	108.2	151.1	412	.0397	1.604	
2	Cd	154.0	151.1	2±1	.0414	0.007	
3	Cd	0.0	74.9	454	.0337	2.082	
4	Cd	0.0	36.8	5±1	.0379	0.020	
5	Cd	0.0	181.5	762	.0411	2.865	
6	Cd	0.0	120.6	781	.0400	3.017	
7	Cd	91.4	151.1	729	.0389	2.896	

TABLE 4.14

Power Normalization Factors - Configuration 1

Run	Time	Decay Time (min)	Decay Factor	Activity (CPM)	Corrected Activity (CPM) (1)	Norm. Factor
1002	1116.46	24.02	.460	172661	79424	1.000
	1117.75	25.31	.480	165687	79530	
	1119.03	26.59	.500	158877	79438	
				Avg.	79464	
1003	1539.24	17.87	.360	239417	86190	0.935
	1540.48	19.11	.375	223496	83811	
	1541.73	20.36	.400	212101	84840	
				Avg.	84947	
1004	1611.24	39.67	.760	113245	86066	0.917
	1612.58	41.01	.800	109193	87354	
	1613.90	42.33	.820	105261	86314	
				Avg.	86578	
1005	1549.38	23.91	.450	183674	82653	0.958
	1550.88	25.41	.480	173263	83166	
	1552.20	26.73	.500	166093	83047	
				Avg.	82955	
1006	1246.53	68.27	1.45	60963	88396	0.909
	1247.84	69.58	1.48	58803	87028	
	1249.09	70.83	1.51	57529	86869	
				Avg.	87431	
	1305.80	87.54	1.95	44382	86545	0.922
	1307.08	88.82	1.975	43736	86379	
	1308.38	90.12	2.00	42884	85768	
				Avg.	86231	
1007	1416.95	41.23	0.81	106951	86630	0.926
	1418.33	42.61	0.825	103740	85586	
	1419.62	43.90	0.850	100256	85218	
				Avg.	85811	
1008	1549.68	25.17	0.47	175855	82652	0.952
	1551.01	26.50	0.50	167467	83734	
	1552.27	27.76	0.52	160140	84075	
				Avg.	83487	
1009	1501.76	33.44	0.63	80406	50656	1.554 (2)
	1503.08	34.76	0.66	77804	51351	
	1504.33	36.01	0.68	75566	51385	
				Avg.	51131	

Position 44.4 in end reflector Run 1003/1009 = 0.958

$$.958 \times .935 = .896$$

(1) Activity decay corrected to 50 min. after shutdown.

(2) The normalizer data for this run were obviously in error. No explanation could be found for the bad data. Since a gold foil was exposed at the same position on Runs 1003 and 1009, the counts from these foils were used to determine the normalization factor for Run 1009 of .896.

TABLE 4.15

Gold Foil Cadmium Ratios and Thermal Neutron Flux - Configuration 1

Location		Bare	Cd	Cd	Corrected	Thermal Flux
Radial (cm)	Axial (cm)	d/m/gm $\times 10^{-5}$	d/m/gm $\times 10^{-5}$			
0	0	0.35	.00013(1)	2692	1225	0.15
0	13.9	2.43	0.0010(1)	2430	1204	1.18
0	29.1	5.68	0.0080(1)	710	325	2.55
0	36.8	8.43	0.0204	413.2	172.59	3.55
0	44.4	9.92	0.0757	131.0	53.42	4.15
0	59.6	14.02	0.482	29.09	12.75	5.70
0	74.9	16.59	2.08	7.98	4.04	6.12
0	89.4	9.81	3.18	3.08	1.88	2.81
0	90.1	9.13	3.25	2.81	1.82	2.54
0	120.6	8.41	3.02	2.78	1.73	2.28
0	151.1	8.37	2.92	2.87	1.74	2.27
0	181.5	8.57	2.87	2.99	1.75	2.26
0	212.0	8.91	3.30	2.70	1.84	2.56
0	151.1	8.37	2.92	2.87	1.74	2.27
61.0	151.1	8.97	3.02	2.97	1.78	2.39
91.4	151.1	9.77	2.90	3.37	1.96	2.86
93.7	151.1	11.66	3.01	3.87	2.06	3.57
108.2	151.1	15.34	1.60	9.59	4.44	5.70
123.5	151.1	11.60	0.301	38.54	15.91	4.76
138.7	151.1	7.79	0.0405	192.3	83.23	3.27
154.0	151.1	4.71	0.005(1)	942	388	1.99
169.2	151.1	2.50	.0007(1)	3571	1470	1.05
184.4	151.1	0.71	.00008(1)	8875	3636	0.30
91.4	90.1	9.63	3.34	2.88	2.05	2.81
91.4	212.0	9.90	3.58	2.77	2.07	2.73

(1) These are extrapolated values.

Fig. 4.1 Fuel tray installation pattern and nomenclature

Fig. 4.2 Initial fuel loading recipe for cavity reactor

Fig. 4.3 Inverse multiplication curve, configuration 1, average of three channels

Fig. 4.4 Relationship between the most probable and average path length for various values of variance

Fig. 4.5 Subcritical rod worth curves - configuration 1

Fig. 4.6 Radial power profile from bare catcher foils - configuration 1

Fig. 4.7 Axial power profile from bare catcher foils - configuration 1

Fig. 4.8 Radial power profile from bare catcher foil showing effects of position on a tray surface

Fig. 4.9 Radial distribution of bare gold foil activity in the cavity at an axial position of 151.2 cm - configuration 1

Fig. 4.10 Axial distribution of bare gold foil activity in the cavity at core center - configuration 1

Fig. 4.11 Bare gold foil activity distribution in the reflector - configuration 1

Fig. 4.12 Gold-cadmium ratios in the radial and end reflectors - configuration 1

Fig. 4.13 Thermal neutron flux distribution radially through axial center of core - configuration 1

Fig. 4.14 Thermal neutron flux distribution axially through radial center of core - configuration 1

5.0 CONFIGURATION 2

Prior to reducing the fuel radius, a modification was made to the fuel tray arrangement to give overlap of adjacent trays and thus reduce the streaming paths between trays. The modification is illustrated in Figure 5.1. There were two 1.27 cm diameter aluminum tubes placed near the front and rear of each fuel tray as shown in Figure 5.1. These tubes ran through the center of each tray and supported the trays on rails at both sides. The 30.5 cm diameter end plug was in the reactor and only D_2O in the reflector region.

5.1 Initial Loading

The test required a fuel to cavity radius ratio of 0.4. The surfaces on which fuel was to be placed are shown in Figure 5.2. There were a total of 180 fuel surfaces within the desired fueled radius. It takes 16 sheets of fuel to completely cover a single surface of a fuel tray leaving gaps only where the two support tubes pass through the trays. Two sizes of fuel sheets were used in loading this reactor. Because of the anticipated heavy loading, the larger or 1.5 size fuel sheets (7.30 x 10.95 cm by 0.00254 cm thick) were used as much as possible. As explained previously, a normal 1.0 size fuel sheet was 7.30 cm square by 0.00254 cm thick so a 1.5 size sheet is 1.5 times longer and weighs approximately 1.5 times the 1.0 size sheet. Unless otherwise stated, all given numbers of sheets of fuel in the reactor will be in equivalent 1.0 size sheets.

Initial loading began with a completely unloaded core. Each surface was to be loaded with three layers of fuel or 48 fuel sheets per surface giving a total of 8640 sheets of fuel when fully loaded. Normal loading procedures were followed as the above fuel was placed in the reactor. The inverse multiplication data obtained are given in Table 5.1 and Figure 5.3. As will be noted, the reactor was still substantially subcritical with 8640 sheets of fuel (22.72 kg) in the cavity. Extrapolation of the curve indicated that it would take in excess of 34 kg of fuel to go critical. Since the curves were still flattening out, there was little indication where the reactor would actually be critical.

After consulting with the NASA representative, it was decided to increase the fuel radius until a critical mass was reached without exceeding about 24 kg of fuel in the reactor. The fuel radius was first increased to 0.465 of the fuel cavity radius and the extrapolated critical loading was about 9700 sheets of fuel or 25.3 kg of fuel. This extrapolation was made on the basis of $0.84 \times 10^{-3} \% \Delta k / \text{gm}$ and an estimate of $4.27 \% \Delta k$ subcritical. This value is estimated to be uncertain by about -1, +4 kg. Since the fuel loading for this fuel radius extrapolated to more than 24 kg the fuel radius was further expanded to 0.53 of the cavity radius as shown in Figure 5.4. There was a total of 324 fuel tray surfaces, on which fuel was placed, with an average of 24 sheets per surface for a total of 7776 fuel sheets or 20.4 kg of fuel in the reactor when fully loaded as shown in Table 5.1. This gave an average fuel thickness per fuel tray of 0.00381 cm. Each fuel surface contained one solid layer of fuel (16 sheets) plus an additional 8 sheets equally

spaced and staggered from one tray to the next thus equally dispersing the fuel throughout the active core. The inverse multiplication data are given in Table 5.1. Average excess reactivity was $0.981 \pm 0.022\% \Delta k$ as given in Table 5.2 with 7776 sheets of fuel in the reactor based on four separate measurements as shown in Table 5.2. The aluminum screen support structure including the frame, screens and hold-down straps weighed approximately 122 kg.

5.2 Rod Calibrations and Reactivity Measurements

5.2.1 Rod Calibrations

No additional relative rod shape curves were measured for this configuration. It was assumed that the subcritical curves obtained on Configuration 1 would be valid for the reduced fuel radius. However, three of the actuators were calibrated as well as all rods as a bank for absolute worth. The data are presented in Table 5.2. The single measurement with all rods equally withdrawn gave a 10% lower k-excess value than the other measurements using two actuators.

5.2.2 Material Worth Measurements

The reactivity worth of fuel was measured in various positions in the reactor. The values obtained are given in Table 5.4. Compared to Configuration 1, the fuel worth at the core center decreased a factor of 2.9 and the fuel worth at the outer edge decreased a factor of 2.2.

5.3 Power Distribution Measurements

5.3.1 Bare Catcher Foils

The radial and axial power distributions in the active core obtained from bare catcher foils are given in Table 5.5 and Figures 5.5 and 5.6. These foil exposures were made with all rods withdrawn except actuator 6 which was about 39 cm withdrawn and at an average D_2O temperature of $25^\circ C$. The ratio of the radial power from the outside of the fuel to the center of the core at the axial center of the cavity was about 2.85 compared to 1.18 for Configuration 1. The weighted average radial power distribution of 1.54 is 43% higher than for Configuration 1. The greater flux attenuation was, of course, due to the heavier fuel loading compacted in a smaller volume for Configuration 2. The axial power distribution also showed greater power gradients from the end to the center of the core for Configuration 2 than for Configuration 1. The ratio of the power at the control rod end of the cavity to the center of the cavity was 1.98 for this configuration compared to 1.16 for Configuration 1. The same ratio at the separation plane was 1.76 compared to 1.10 for Configuration 1. The average value for the axial power distribution was 1.165 or 12% higher than for Configuration 1.

It will be noted that at an axial position around 135.8 cm, the axial power profile shows a high point. This point occurs at the position of one of the aluminum tubes used to support the fuel screens. These tubes were lined up near the same axial position for all trays thus creating a low absorption path for neutrons through this region. The flux pattern over this area was measured with 0.635 cm diameter

catcher foils and the results are shown graphically in Figure 5.7. At 135.8 cm from the end of the core where the 1.429 cm diameter foil was normally placed, the power was about 10% above the point at 143.7 cm. This agrees very well with Figure 5.6. The 10 cm spread of the peak (FWHM) was surprising, since the data were from the center of the reactor, the beam of neutrons should have been well collimated within the width of the gap which was approximately 1.3 cm wide, assuming the support tubes were perfectly lined up.

5.3.2 Cadmium Ratios - Catcher Foils

The cadmium covered catcher foil data are given in Table 5.5. The cadmium ratios obtained from the bare and cadmium covered foils are presented in Table 5.6. Figures 5.8 and 5.9 show both the radial and axial variation in the catcher foil cadmium ratios. The flux is, of course, much harder for this core than with the larger fuel radius. This appears to be true in all positions. There were no cadmium ratios measured in the extreme corners of the cavity for this configuration. There were, however, measurements at both ends of the cavity near the outer radius of the fuel. The cadmium ratios at these points were 22.3.

5.4 Resonance Detector Data - Gold Foils

5.4.1 Bare Gold Foil Data

Gold foil data were obtained from within the cavity and in both the end and radial reflector tanks as was done for Configuration 1. All of the gold data are given in Table 5.7. The relative distributions of the bare data within the cavity are presented in Figures 5.10 and 5.11. As with the catcher foil data, the gold activation neutron flux distribution in the core was significantly changed due to reducing the fuel radius and increasing the fuel density. The ratio of the gold activation at the outer edge of the fuel to the core center at the axial mid-plane was 1.63 compared to about 1.13 for Configuration 1.

It will be noted from Figure 5.10 that the point at 151.1 cm, the normalization point, is about 4% below the expected smooth curve. This is the same point as at the core center on the radial plot (Figure 5.9) which appears to be in line with the other radial data points. There is no apparent reason for this anomaly. Taking the points as they are shown in the figure, the values at the ends of the core are about 38% higher than for Configuration 1.

The gold activation flux distribution in the end and radial reflectors are shown in Figure 5.12. The power normalized gold foil disintegration rates are still normalized to Run 1002 and the normalization data is listed in Table 5.8. If there were no changes in the relationship of the normalizer foils to reactor power with the new fuel radius and core loading, a comparison could be made directly with Configuration 1. However, the altered flux distribution in the core changes the ratio of total core power to normalizer specific power. The average catcher foil normalized activity at the core center was 39111 counts. Using the same procedure as given in Section 4.4.1, the following specific

power is calculated for the core center:

$$\frac{39111 \times 79464 \times 123.2}{100000 \times 3.2 \times 10^{10}} = 1.20 \times 10^{-4} \text{ watts/gm U-235}$$

The total reactor power is then calculated by factoring in the weighted radial average, the longitudinal average and the total fuel mass in the reactor as follows:

$$1.20 \times 10^{-4} \times 1.540 \times 1.165 \times 20.4 \times 10^3 \times 0.932 = 4.09 \text{ watts}$$

This compares to the normalized power for Configuration 1 of 3.63 watts. If the gold foil disintegration rates are corrected for the 13% difference in reference power as noted above, the end reflector results show little or no change compared to Configuration 1. The radial reflector, however, was about 11% lower than the same results from Configuration 1.

5.4.2 Cadmium Ratio - Gold Foils

The cadmium ratios obtained from the bare and cadmium covered foil data are presented in Table 5.9. The ratios were corrected to infinitely dilute values as described for Configuration 1, see Section 4.4.2. Within the fueled region, the cadmium ratio decreased by 20 to 25% from the values obtained for Configuration 1. The cadmium ratios in the end and radial reflectors are shown in Figure 5.13. The ratios in the radial reflector were essentially unchanged from Configuration 1. However, the ratio in the end reflector was consistently lower by $(20 \pm 10)\%$.

5.4.3 Thermal Neutron Flux Distribution - Gold Data

The bare and cadmium covered gold foil data obtained from Configuration 2 was used in calculating thermal neutron flux as was done on Configuration 1 and explained in Section 4.4.3. The results are presented in Table 5.9, and Figures 5.14 and 5.15. Where points of direct comparison could be made, the ratio of Configuration 2 to Configuration 1 was calculated and these ratios are shown in Table 5.9. It will be noted here that at the center of the core the thermal flux was reduced about 70%. The thermal flux in the radial reflector was reduced about $12 \pm 2\%$. The end reflector showed a lower thermal flux level near the cavity wall with a gradual increase above that measured for Configuration 1 beyond about 30 cm from the cavity wall.

TABLE 5.1

Inverse Multiplication - Configuration 2

CPM Increment	Total Fuel (Sheets)	Channel 1 CPM	CRo/CR	Channel 2 CPM	CRo/CR	Channel 3 CPM	CRo/CR	Avg.	Rod Positions
0	0	642		1274		619			in-table open
0	0	347		505		330			in
0	0	378		556		371			out
1	1152	715	.898	1360	.937	657	.942	.926	in-table open
1	1152	574	.605	853	.592	537	.615	.604	in
1	1152	659	.574	962	.578	629	.590	.581	out
2	2112	731	.475	1069	.472	691	.478	.475	in
3	2304	717	.854	1416	.900	690	.897	.884	in-table open
3	2304	754	.460	1091	.463	730	.452	.458	in
3	2304	902	.419	1343	.414	871	.426	.420	out
4	3456	773	.831	1417	.899	726	.853	.861	in-table open
4	3456	969	.358	1417	.356	930	.355	.356	in
4	3456	1185	.319	1766	.315	1154	.321	.318	out
5	4608	766	.838	1490	.855	722	.857	.850	in-table open
5	4608	1208	.287	1791	.282	1160	.284	.284	in
5	4608	1553	.243	2262	.246	1503	.247	.245	out
6	5472	786	.817	1546	.824	767	.807	.816	in-table open
6	5472	1528	.227	2213	.228	1444	.229	.227	in
6	5472	2023	.187	2993	.186	1943	.191	.188	out
7	6336	830	.773	1536	.829	751	.824	.809	in-table open
7	6336	1781	.195	2666	.189	1738	.190	.191	in
7	6336	2521	.150	3755	.148	2435	.152	.150	out
8	7104	818	.785	1562	.816	773	.801	.801	in-table open
8	7104	2016	.172	3019	.167	1954	.169	.169	in
8	7104	2991	.126	4546	.122	2917	.127	.125	out
9	7968	826		1583		776			in-table open
9	7968	2407	.144	3609	.140	2391	.138	.141	in
9	7968	3954	.096	5850	.095	3818	.097	.096	out
10	8640	2778	.125	4173	.121	2742	.120	.122	in
10	8640	4738	.080	7030	.079	4603	.081	.080	out
Removed one layer of fuel from Trays 16 and 17.									
11	8256	2622	.132	3873	.130	2500	.132	.131	in
11	8256	4430	.085	6587	.084	4268	.087	.085	out

TABLE 5.1
(Continued)

CPM Increment	Total Fuel (Sheets)	Channel 1 CPM CRO/CR	Channel 2 CPM CRO/CR	Channel 3 CPM CRO/CR	Avg.	Rod Positions
Added two fuel layers to two surfaces of Trays 16 and 17 plus 4 surfaces to Trays 7 and 27. This was the initial step in changing to a fuel to cavity radius ratio of .465.						
12	8640	2968 .117	4441 .114	2876 .115	.115	in
12	8640	5612 .067	8251 .067	5310 .070	.068	out
Reduced fuel to two layers (32 per surface) on Trays 10, 15, 18, 24. Added two surfaces to 10, 15, 18, 24.						
13	8256	3039 .114	4525 .112	2920 .113	.113	in
13	8256	5814 .065	8431 .066	5498 .067	.066	out
Added one fuel layer to Tray 12.						
14	8416	3122 .111	4578 .110	2962 .111	.111	in
14	8416	5912 .064	8669 .064	5634 .066	.065	out
Changed Trays 11, 12, 13, 14, 19, 20, 21, 22 and 23 to 32 sheets/surface. Trays 11, 12, 13, 21, 22 and 23 now 12 surfaces and Trays 14, 19 and 20 now 14 surfaces.						
15	7296	3107 .112	4504 .112	2936 .112	.112	in
15	7296	5777 .065	8497 .065	5547 .067	.066	out
Changed Tray 25 to 10 surfaces, Tray 26 to 8 surfaces, Tray 27 to 6 surfaces and added Tray 28 with 2 surfaces, all with 32 sheets/surface.						
16	7520	3426 .101	5080 .099	3262 .101	.100	in
16	7520	7154 .053	10513 .053	6677 .056	.054	out
Changed Tray 9 to 10 surfaces, Tray 8 to 8 surfaces, Tray 7 to 6 surfaces and added Tray 6 with 2 surfaces. All 244 surfaces contain 32 sheets of fuel.						
17	7744	4072 .085	5965 .085	3856 .086	.085	in
17	7744	9312 .041	13513 .041	8575 .043	.042	out
The fuel to cavity radius ratio is now .465.						
Added one surface to each side of Trays 14, 15, 16, 17, 18, 19 and 20 with 32 sheets/surface. This is the first step in changing to a fuel to cavity radius ratio of .53.						
18	8192	5138 .068	7638 .066	4988 .066	.067	in
18	8192	20505 .018	29762 .019	19135 .019	.019	out
Added one layer of fuel to all 12 surfaces on Tray 12.						
19	8384	5425 .064	7993 .063	5096 .065	.064	in
19	8384	24336 .016	35204 .016	22489 .016	.016	out
Removed one layer of fuel from every other surface on Trays 14, 15, 16, 17, 18, 19 and 20.						
20	7488	4212 .082	6187 .082	3971 .083	.082	in
20	7488	11180 .034	16404 .034	10483 .035	.034	out

TABLE 5.1
(Continued)

CPM Increment	Total Fuel (Sheets)	Channel 1 CPM CRO/CR	Channel 2 CPM CRO/CR	Channel 3 CPM CRO/CR	Avg.	Rod Positions
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Modified Trays 21 to 28 to 1 layer on every other surface and two layers on others.
Added Tray 29 in same manner.

21	7728	6020	.0576	8950	.0564	5705	.0578	.0573	in
21	7728	38223	.0099	56387	.0099	35628	.0104	.0101	out

Changed Trays 7, 8, 9, 10, 11, 12 and 13 to one layer of fuel on every other surface. Changed Tray 7 to 10 surfaces, Trays 8 and 9 to 12 surfaces, Trays 10, 11 and 12 to 14 surfaces and Tray 13 to 16 surfaces.

22	7504	6945	.050	10279	.049	6586	.050	.050	in
22	7504	243290	.0016	315690	.0018	212471	.0017	.0017	out

Changed Tray 6 to 8 surfaces and one layer of fuel to every other surface.

23	7632	8205	.042	11570	.044	7480	.044	.043	in
----	------	------	------	-------	------	------	------	------	----

Critical k-excess = $0.392 + 0.007\% \Delta k$

Added Tray 5.

24	7776	10386	.033	13575	.037	8691	.038	.036	in
----	------	-------	------	-------	------	------	------	------	----

Critical k-excess = $0.981 \pm 0.022\% \Delta k$

TABLE 5.2
Rod Worth and Excess Reactivity - Configuration 2

Run No.	Actuator No. Being Evaluated	Rod Worth (% Δk)	k-excess Based on Average Rod Worth (% Δk)
36 (1)	6 (3 rods)	-0.7644	0.3924
37 (2)	4 (2 rods)	-0.6135	0.9714
38	6 (3 rods)	-0.7383	0.9958
39	4 (2 rods)	-0.5791	0.9657
40	1 (3 rods)	-1.0680	0.9897
41	All rods (17)	-4.6080	0.8870

Average Worth of Actuator 6 = -0.751 ± 0.013

Average Worth of Actuator 4 = -0.596 ± 0.017

- (1) Tray 5 out of reactor
(2) Tray 5 in reactor from Run 37 to Run 41

TABLE 5.3

Critical Fuel Tray Loading Arrangement - Configuration 2B

Tray No.	Number of Surfaces	Fuel Sheets per Tray (1)	Fuel Weight (2) (gm)
5	6	144	377.3
6	8	192	503.0
7	10	240	628.8
8	12	288	754.6
9	12	288	754.6
10	14	336	880.3
11	14	336	880.3
12	14	336	880.3
13	16	384	1006.1
14	16	384	1006.1
15	16	384	1006.1
16	16	384	1006.1
17	16	384	1006.1
18	16	384	1006.1
19	16	384	1006.1
20	16	384	1006.1
21	16	384	1006.1
22	14	336	880.3
23	14	336	880.3
24	14	336	880.3
25	12	288	754.6
26	12	288	754.6
27	10	240	628.8
28	8	192	503.0
29	6	144	377.3
Total	324	7776	20373.3

(1) Equivalent 1.0 size fuel sheets 7.30 cm square by 0.00254 cm thick.

(2) Weights are based on 2.62 grams per fuel sheet.

TABLE 5.4
Fuel Worth Measurements - Configuration 2

Position	Fuel Change (grams)	k-excess Change (% Δ k)	Fuel Worth (% Δ k/gm)
One layer removed from Trays 5, 13, 21, 29	760.2	-0.675	.888 x 10 ⁻³
One layer of fuel from two surfaces of Trays 8 and 26	160.4	-0.143	.892 x 10 ⁻³
Center of Core	159.3	-0.0849	.533 x 10 ⁻³
Outer edge of core (trays)	377.0	-0.579	1.536 x 10 ⁻³

TABLE 5.5
Catcher Foil Data - Configuration 2

Run 1010

Foil No.	Type	Location		Tray No.	Normalized Counts (l)	Ratio of Local to Core Center (Foil No. X)
		Radial (cm)	Axial (cm)			
1	Bare	0	212.0	17	64576	1.650
2	Bare	0	196.8	17	30286	0.774
3	Bare	0	181.5	17	41592	1.063
4	Bare	0	166.3	17	40088	1.024
5	Bare	0	151.1	17	39130	1.000 (X)
6	Bare	0	135.8	17	42748	1.092
7	Bare	0	120.6	17	40869	1.044
8	Bare	0	105.3	17	44105	1.127
9	Bare	0	90.1	17	77464	1.980
10	Bare	15.9	212.0	17	74695	1.909
11	Bare	15.9	181.5	17	45528	1.164
12	Bare	15.9	151.1	17	43746	1.118
13	Bare	15.9	120.1	17	45772	1.170
14	Bare	15.9	90.1	17	81057	2.071
15	Bare	27.9	212.0	17	81746	2.089
16	Bare	27.9	181.5	17	52814	1.350
17	Bare	27.9	151.1	17	50458	1.289
18	Bare	27.9	120.6	17	52677	1.346
19	Bare	27.9	90.1	17	86505	2.211
20	Bare	38.7	212.0	17	92567	2.366
21	Bare	38.7	181.5	17	67358	1.721
22	Bare	38.7	151.1	17	64268	1.642
23	Bare	38.7	120.6	17	63552	1.624
24	Bare	38.7	90.1	17	99651	2.547
25	Bare	46.4	212.0	17	104028	2.658
26	Bare	46.4	181.5	17	91929	2.349
27	Bare	46.4	151.1	17	79988	2.044
28	Bare	46.4	120.6	17	86777	2.218
29	Bare	46.4	90.1	17	123048	3.145
30	Bare	50.8	212.0	17	123391	3.153
31	Bare	50.8	181.5	17	114993	2.939
32	Bare	50.8	151.1	17	115185	2.944
33	Bare	50.8	120.1	17	121256	3.099
34	Bare	50.8	90.1	17	135366	3.459
35	Bare	55.2	212.0	17	123630	3.181
36	Bare	55.2	181.5	17	118485	3.053

TABLE 5.5
(Continued)

Run 1010 (Cont'd)

Foil No.	Type	Location		Tray No.	Normalized Counts (l)	Ratio of Local to Core Center (Foil No. X)
		Radial (cm)	Axial (cm)			
37	Bare	55.2	151.1	17	119303	3.074
38	Bare	55.2	120.6	17	124175	3.200
39	Bare	55.2	90.1	17	134043	3.454
40	Bare	46.4	212.0	19	98817	2.546
41	Cd	46.4	90.1	19	4795	---
42	Bare	43.8	90.1	19	106804	2.752
43	Cd	43.8	212.0	19	4441	---

Run 1011

8	Cd	0	212.0	17	4860	---
9	Cd	0	120.6	17	4152	----
10	Cd	44.5	151.1	17	4503	---

Run 1012

1	Cd	0	181.1	17	4165	---
2	Cd	0	90.1	17	5044	---
3	Cd	27.9	151.1	17	4353	---
4	Bare	0	212.0	17	68451	1.751
5	Bare	0	206.9	17	58973	1.509
6	Bare	0	201.9	17	55724	1.425
7	Bare	0	196.8	17	48935	1.252
8	Bare	0	181.5	17	41068	1.051
9	Bare	0	166.3	17	41038	1.050
10	Bare	0	151.1	17	39092	1.000 (X)
11	Bare	0	135.8	17	43177	1.104
12	Bare	0	120.6	17	41914	1.072
13	Bare	0	105.3	17	47230	1.208
14	Bare	0	100.3	17	48336	1.236
15	Bare	0	95.2	17	62081	1.588
16	Bare	0	90.1	17	77483	1.982
17	Bare	0	212.0	17	72341	1.851
18	Bare	5.1	212.0	17	73754	1.887
19	Bare	10.2	212.0	17	75661	1.935
20	Bare	15.2	212.0	17	78471	2.007
21	Bare	20.3	212.0	17	79799	2.041
22	Bare	25.4	212.0	17	82988	2.123
23	Bare	30.5	212.0	17	88779	2.271

TABLE 5.5
(Continued)

Run 1012 (Cont'd)

Foil No.	Type	Location		Tray No.	Normalized Counts (1)	Ratio of Local to Core Center (Foil No. X)
		Radial (cm)	Axial (cm)			
24	Bare	35.6	212.0	17	95911	2.453
25	Bare	40.6	212.0	17	106546	2.726
26	Bare	45.7	212.0	17	119626	3.060
27	Bare	50.8	212.0	17	129904	3.323
28	Bare	55.9	212.0	17	127708	3.267

Run 1013

1	Cd	0	196.8	17	4477	---
2	Cd	0	151.1	17	4164	---
3	Cd	0	105.3	17	4465	---

Run 1016

1	Cd	15.2	151.1	17	4083	---
2	Bare	91.4	212.0	17	131282	3.357 ⁽²⁾
3	Bare	83.8	212.0	17	137932	3.527
4	Bare	76.2	212.0	17	131543	3.364
5	Bare	68.6	212.0	17	132144	3.379
6	Bare	61.0	212.0	17	136456	3.489
7	Bare	53.3	212.0	17	126410	3.232
8	Bare	38.1	212.0	17	94864	2.426
9	Bare	15.2	212.0	17	80876	2.068
10	Bare	0	212.0	17	73424	1.877
11	Bare	91.4	151.1	17	141645	3.622
12	Bare	76.2	151.1	17	141927	3.629
13	Bare	61.0	151.1	17	128537	3.287
14	Bare	53.3	151.1	17	116959	2.991
15	Bare	45.7	151.1	17	78659	2.011

Run 1016 (3)

1	Bare	0	122.4	17	--	--
2	Bare	0	123.2	17	35261	1.026
3	Bare	0	123.9	17	36459	1.061
4	Bare	0	124.7	17	38507	1.120
5	Bare	0	125.4	17	37684	1.096

TABLE 5.5
(Continued)

Run 1016 (Cont'd)

Foil No.	Type	Location		Tray No.	Normalized Counts(1)	Ratio of Local to Core Center (Foil No. X)
		Radial (cm)	Axial (cm)			
6	Bare ⁽¹⁾	0	126.2	17	37222	1.083
7	Bare	0	126.9	17	37061	1.078
8	Bare	0	127.7	17	38237	1.112
9	Bare	0	128.5	17	38232	1.112
10	Bare	0	129.2	17	39132	1.138
11	Bare	0	130.0	17	39311	1.144
12	Bare	0	130.7	17	39163	1.139
13	Bare	0	131.5	17	39282	1.143
14	Bare	0	132.3	17	40017	1.164
15	Bare	0	133.0	17	40362	1.174
16	Bare	0	133.8	17	39472	1.148
17	Bare	0	134.5	17	39625	1.153
18	Bare	0	135.3	17	38823	1.129
19	Bare	0	136.1	17	37479	1.090
20	Bare	0	136.8	17	36602	1.065
21	Bare	0	137.6	17	38247	1.113
22	Bare	0	138.4	17	36597	1.065
23	Bare	0	139.1	17	35860	1.043
24	Bare	0	139.9	17	37879	1.102
25	Bare	0	140.6	17	35352	1.028
26	Bare	0	141.4	17	36018	1.048
27	Bare	0	142.2	17	34905	1.015
28	Bare	0	142.9	17	34718	1.010
29	Bare	0	143.7	17	34381	1.000 (X)

(1) Normalized to 100,000 counts on decay corrector.

(2) Normalized to 39,111 which is average of Runs 1010 and 1012 at center of core.

(3) Foils on Run 1016 were 0.635 cm diameter foils.

TABLE 5.6

Catcher Foil Cadmium Ratios - Configuration 2

Run No.	Location		Tray No.	Normalized Bare Foil Activity	Normalized Cd Foil Activity	Cd Ratio Bare/Cd Activity
	Radial (cm)	Axial (cm)				
1010	46.4	90.1	19	107700	4835	22.3
1010	46.4	212.0	19	99646	4478	22.3
1010-1011	46.4	151.1	17	79988	4503	17.8
1010-1012	27.9	151.1	17	50458	4353	11.6
1010-1016	15.9	151.1	17	43746	4083	10.7
1010-1012	0.0	151.1	17	39130	4164	9.4
1010-1012	0.0	90.1	17	77464	5044	15.4
1010-1011	0.0	120.4	17	40869	4152	9.8
1010-1012	0.0	181.5	17	41592	4165	10.0
1010-1011	0.0	212.0	17	64576	4860	13.3

TABLE 5.7
Gold Foil Data - Configuration 2

No.	Foil Type	Location		Activity (CPM)	Foil Wt. (gm)	Specific Activity d/m/gm x 10 ⁻⁵ (2)
		Radial (cm)	Axial (cm)			
Run 1010						
1	Bare	0	212.0	3930	.0348	6.409
2	Bare	0	196.8	2960	.0331	5.075
3	Bare	0	166.3	3158	.0385	4.655
4	Bare	0	181.5	2562	.0302	4.814
5	Bare	0	151.1	3093	.0399	4.399
6	Bare	0	135.8	3134	.0385	4.620
7	Bare	0	120.6	2346	.0273	4.877
8	Bare	0	105.3	3121	.0348	5.090
9	Bare	0	90.1	4884	.0416	6.663
10	Bare	0	89.4	4546	.0335	7.701
11	Bare	0	74.9	12018	.0376	18.139
12	Bare	0	59.6	10703	.0384	15.818
13	Bare	0	44.4	8159	.0408	11.349
14	Bare	0	29.1	5334	.0415	7.294
15	Bare	0	13.9	2332	.0369	3.587
16	Bare	0	0	291	.0338	0.489
17	Bare	93.7	151.1	6651	.0318	11.870
18	Bare	108.2	151.1	10788	.0409	14.969
19	Bare	123.5	151.1	7215	.0348	11.766
20	Bare	138.7	151.1	4782	.0357	7.602
21	Bare	154.0	151.1	3476	.0418	4.719
22	Bare	169.2	151.1	1684	.0410	2.331
23	Bare	183.7	151.1	367	.0282	0.739
24	Bare	45.7	212.0	5063	.0339	8.476
25	Cd	45.7	90.1	2073	.0385	3.056
26	Bare	45.7	90.1	6120	.0402	8.640
27	Cd	45.7	212.0	2106	.0414	2.887
28	Bare	20.3	151.1	3483	.0431	4.586
29	Bare	31.8	151.1	3915	.0421	5.277
30	Bare	39.4	151.1	3085	.0308	5.684
31	Bare	43.8	151.1	3877	.0341	6.452
32	Bare	50.5	151.1	5162	.0391	7.492
33	Bare	55.9	151.1	5936	.0380	8.865
Run 1011						
1	Cd	93.7	151.1	1950	.0325	3.456
2	Cd	0	44.4	92	.0406	0.131
3	Cd	183.7	151.1	4	.0379	0.006
4	Cd	0	89.4	2074	.0361	3.309
5	Cd	138.7	151.1	33	.0376	0.051
6	Cd	0	0	4	.0367	0.006

TABLE 5.7
(Continued)

Foil No.	Foil Type	Location		Activity (CPM) (1)	Foil Wt. (gm)	Specific Activity
		Radial (cm)	Axial (cm)			d/m/gm x 10 ⁻⁵ (2)
Run 1012						
3	Bare	0	212.0	3704	.0325	6.641
4	Bare	0	151.5	2825	.0360	4.573
5	Bare	0	120.6	2858	.0330	5.047
6	Bare	44.4	151.1	4235	.0356	6.932
7	Cd	108.2	151.1	1151	.0425	1.578
8	Cd	154.0	151.1	9	.0368	0.014
9	Cd	0	74.9	1998	.0399	2.918
10	Cd	0	29.1	12	.0338	0.021
Run 1013						
1	Cd	123.5	151.1	193	.0302	0.366
2	Cd	169.2	151.1	0	.0328	0
3	Cd	0	59.6	479	.0360	0.762
4	Cd	0	13.9	4	.0475	0.005
5	Bare	0	85.0	8612	.0388	12.709
6	Bare	98.1	151.1	7727	.0307	14.411
Run 1014						
1	Bare	103.2	151.1	12682	.0483	15.123
2	Bare	0	79.9	10514	.0354	17.106
3	Cd	0	151.1	1678	.0358	2.700
4	Cd	0	120.6	1842	.0397	2.672
5	Cd	30.5	151.1	1838	.0414	2.557
Run 1015						
1	Cd	0	212.0	2025	.0389	2.972
2	Cd	0	135.8	1827	.0400	2.608
3	Cd	0	90.1	2189	.0411	3.041
4	Cd	31.8	151.1	1746	.0379	2.630
5	Bare	115.9	151.1	8199	.0337	13.889
6	Bare	0	67.2	13163	.0421	17.849
Run 1016						
1	Cd	0	196.8	1806	.0373	2.838
2	Cd	0	105.3	1908	.0390	2.867
3	Cd	44.4	151.1	1885	.0386	2.862

(1) Observed activity corrected to shutdown time.

(2) Specific activity is the disintegration per minute per gram at shutdown normalized for power to Run 1002.

TABLE 5.8
Power Normalization Factors - Configuration 2

<u>Date</u>	<u>Run</u>	<u>Count Time</u>	<u>Decay Time (min)</u>	<u>Decay Factor</u>	<u>Activity (CPM)</u>	<u>Corrected Activity (CPM)(1)</u>	<u>Norm. Factor</u>
6-2-66	1010	1218.10	39.68	0.77	305671	235367	0.336
		1219.34	40.92	0.80	295148	236118	
		1220.58	42.16	0.83	285538	236996	
					Avg.	236160	
6-2-66	1011	1517.86	43.42	0.84	277940	233470	0.341
		1519.28	44.84	0.87	267504	232728	
		1520.86	46.42	0.91	256934	233820	
					Avg.	233336	
6-3-66	1012	1120.84	30.90	0.575	399211	229546	0.345
		1122.09	32.15	0.60	382844	229706	
		1123.33	33.39	0.63	368770	232325	
					Avg.	230526	
6-3-66	1013	1447.84	52.11	1.048	224441	235214	0.339
		1449.08	53.35	1.075	218128	234488	
		1450.33	54.60	1.100	212052	233257	
					Avg.	234320	
6-3-66	1014	1556.78	34.10	0.64	360377	230641	0.341
		1558.32	35.64	0.675	343389	231788	
		1600.31	37.63	0.73	324155	236633	
					Avg.	233021	
6-6-66	1015	1338.28	51.41	1.03	228388	235240	0.338
		1339.53	52.66	1.06	221931	235247	
		1340.77	53.90	1.085	215866	234215	
					Avg.	234901	
6-6-66	1016	1604.47	23.95	0.46	501278	230588	0.347
		1605.78	25.26	0.475	479665	227841	
		1607.02	26.50	0.50	458337	229168	
					Avg.	229199	

(1) Activity decay corrected to 50 min. after shutdown.

TABLE 5.9

Gold Foil Cadmium Ratios and Thermal Neutron Flux - Configuration 2

Location		Bare	Cd	Cd	Corrected	Thermal Flux	
Radial (cm)	Axial (cm)	d/m/gm $\times 10^{-5}$	d/m/gm $\times 10^{-5}$			A (1)	B (2)
0	0	0.489	0.0006(3)	815	351	0.19	1.268
0	13.9	3.587	0.0036(3)	996	429	1.36	1.153
0	29.1	7.294	0.0207	352	154	2.77	1.086
0	44.4	11.349	0.1305	87	36	4.27	1.029
0	59.6	15.818	0.762	20.76	9.41	5.74	1.007
0	74.9	18.139	2.918	6.22	3.12	5.76	0.941
0	89.4	7.701	3.309	2.33	1.55	1.63	0.580
0	90.1	6.663	3.041	2.191	1.48	1.38	0.543
0	105.3	5.090	2.867	1.775	1.30	0.79	--
0	120.6	4.877	2.672	1.825	1.27	0.67	0.294
0	135.8	4.620	2.608	1.771	1.31	0.75	--
0	151.1	4.399	2.700	1.629	1.29	0.69	0.304
0	196.8	5.075	2.838	1.788	1.31	0.80	--
0	212.0	6.409	2.972	2.156	1.46	1.25	0.488
0	151.1	4.399	2.700	1.629	1.29	0.69	0.304
31.8	151.1	5.277	2.630	2.006	1.44	1.05	--
43.8	151.1	6.452	2.862	2.254	1.50	1.31	--
93.7	151.1	11.869	3.456	3.43	2.07	3.19	0.894
108.2	151.1	14.969	1.578	9.49	4.36	5.09	0.893
123.5	151.1	11.766	0.366	32.15	15.24	4.35	0.914
138.7	151.1	7.602	0.506	150	63	2.87	0.878
169.2	151.1	2.331	0.0028(3)	833	359	0.89	0.848
183.7	151.1	0.739	0.0005(3)	1449	637	0.28	0.933
45.7	212.0	8.476	2.887	2.94	1.74	1.50	--
45.7	90.1	8.640	3.056	2.83	1.76	1.50	--

- (1) Column A gives the thermal flux in $n/cm^2/sec/watt \times 10^{-6}$ for Configuration 2.
 (2) Column B is the ratio of thermal flux in Configuration 2 to Configuration 1.
 (3) These are extrapolated values.

Fig. 5.1 Fuel tray arrangement - configuration 2

Fig. 5.2 Fuel tray installation pattern and nomenclature - configuration 2A

Fig. 5.3 Inverse multiplication curve - configuration 2 - average of three channels

Fig. 5.4 Fuel tray installation pattern and nomenclature - configuration 2B

Fig. 5.5 Radial power profile from bare catcher foils at an axial position at 151.1 cm and at separation plane - configuration 2

Fig. 5.6 Axial power profile from bare catcher foils at core center - configuration 2

Fig. 5.7 Axial power profile over fuel gap due to aluminum support tube - configuration 2

Fig. 5.8 Catcher foil cadmium ratio radial profile at an axial position of 151.1 cm - configuration 2

Fig. 5.9 Catcher foil cadmium ratio axial profile at core center - configuration 2

Fig. 5.10 Radial distribution of bare gold foil activity in the cavity at an axial position of 151.1 cm - configuration 2

Fig. 5.11 Axial distribution of bare gold foil activity in the cavity at core center - configuration 2

Fig. 5.12 Bare gold foil activity distribution in the reflector - configuration 2.

Fig. 5.13 Gold cadmium ratios for the radial and end reflectors - configuration 2

Fig. 5.14 Thermal neutron flux distribution radially through axial center of core - configuration 2

Fig. 5.15 Thermal neutron flux distribution axially through radial center of core - configuration 2

6.0 CONFIGURATION 3A

The only change in going from Configuration 2 to this assembly was in the fuel radius. The fueled region was extended from 0.53 to 0.67 of the full cavity radius. The 12-in. diameter plug was still in the movable reflector tank, as with the previous configuration and only D₂O was in the reflector regions. The reason for using "3A" as the configuration identification is that measurements were also made with this same fuel radius but with the 12-diameter plug removed, and this arrangement will be identified as Configuration 3B.

6.1 Initial Loading

Based on the previous results, it was anticipated that it would take around 5500 sheets of fuel to go critical at a fuel radius of 24 inches. At this fuel radius, there were 504 surfaces on which fuel could be placed as shown in Figure 6.1. After making a preliminary check on the reactivity change caused by increasing the fuel radius on three trays and changing the number of fuel sheets per tray from Trays 24 to 11, the entire fuel loading was changed to the desired fuel radius and 11 sheets per fuel surface. This change was made by modifying configuration 2 and not by inverse multiplication. With the changeover completed and 5544 sheets of fuel in the reactor (14.5kg of Orallo), k-excess was 0.0367%Δk. This k-excess value was measured with all rods in the withdrawn position.

The fuel weight is based on an average sheet weight of 2.62 gm. The fuel was placed on the trays as shown in Figure 6.2 and Table 6.1. As seen from this figure, two fuel arrangements were used. All of the surfaces on a given tray were loaded with a single arrangement and the tray loading was alternated so that the loading was staggered through the core. It will also be noted that there were six 1.5 size sheets and two 1.0 size sheets of fuel per surface giving the equivalent of eleven 1.0 size sheets per surface.

6.2 Rod Calibrations and Reactivity Measurements

6.2.1 Rod Calibrations

Rod calibrations on this configuration were minimal. A single rod "bump" was performed on Actuators 1, 4 and 6 and their measured worths were -1.046, -0.605 and -0.777%Δk respectively. The measurements were based on the subcritical rod worth curve for actuator 4 given in Section 4.2.1.

6.2.2 Material Worth Measurements

Two fuel worth measurements were obtained at the outer edge of the fueled region at the axial midplane of the core. The results gave $(1.513 \pm 0.20) \times 10^{-3}\% \Delta k / \text{gm}$ and $(2.46 \pm 0.30) \times 10^{-3}\% \Delta k / \text{gm}$. The average of these two values is obviously outside of the standard error given. Repeat measurements were not made to determine which of the above values was in error. However, the latter value appears to be more in line with the power distribution data for the ratio of core center

to outer edge fuel. The standard error given is based on $0.007\% \Delta k$ variation for a set of two reactivity measurements, i.e., the measurement before and after the change to the system. A fuel worth measurement was also made at the core center on tray 17. The value was $(1.25 \pm 0.25) \times 10^{-3} \% \Delta k / \text{gm}$.

Because of uncertainty in worth of the aluminum end plates in the two reflector tanks at the separation plane, a special piece of aluminum was cut to fit in the crack at the separation plane and its reactivity worth was measured. The aluminum sheet was 0.08128 cm thick, weighed 4.42 kg, and covered 25.6% of the 360 degrees annulus formed by the fixed radial reflector tank at the separation plane. The presence of this sheet of aluminum caused k-excess to decrease $0.0143 \pm 0.010 \% \Delta k$. This is an assumed error based on a standard error of $0.007 \% \Delta k$ per reactivity measurement. This extrapolates to $0.056 \pm 0.039 \% \Delta k$ decrease in reactivity for 360 degrees. Each end of the reflector tanks was 1.27 cm thick. The total aluminum worth of the end plates over the 91.4 cm thick radial reflector region at the separation plane would, therefore, extrapolate to be worth about $-1.750 \pm 1.221 \% \Delta k$. Additional data on the table separation plane is discussed in Section 4.2.3.

6.3 Power Distribution Measurements

6.3.1 Bare Catcher Foils

Prior to power mapping, k-excess was increased by adding a small amount of fuel to the outer surface of the core. A 1.5 size fuel sheet was added to the outer fuel surface on each side of trays 1, 4, 8, 12, 16, 20, 24, 30, 32 and to one side only of tray 26 for a total of nineteen 1.5 size sheets. These were dispersed along the length of the active core and represented an addition of about 74.7 gm. Power mapping was performed with all rods withdrawn except actuator 6 which was, on an average, 41 cm withdrawn. The D_2O temperature was nominally 25°C .

The power distribution data obtained within the cavity with bare catcher foils are given in Table 6.2. The power distribution resulting from the bare catcher foil data are presented in Figures 6.3 and 6.4. As would be expected the radial power distribution falls between that obtained for Configuration 1 and 2. The ratio of the power at the active core edge to core center at the axial mid-plane was about 1.9 compared to 1.18 for Configuration 1 and 2.85 for Configuration 2. The weighted average radial power at the axial center of the core was 1.444 compared to 1.079 and 1.540 for Configurations 1 and 2, respectively.

The axial power profile also falls between Configurations 1 and 2. The peak power at the reference end and radial center of the core was 1.45 times the core center power. This factor was 1.37 at the other end of the core. These same factors were 1.16 and 1.98 for the control rod end of the core and 1.10 and 1.76 at the separation plane for Configurations 1 and 2, respectively. The average axial profile at the radial

center for each of the three configurations, in order, was 1.036, 1.165 and 1.065 with Configuration 3A again falling between Configurations 1 and 2, as would be expected.

6.3.2 Cadmium Ratios - Catcher Foil

Sufficient cadmium covered catcher foil data were obtained within the cavity to define the radial and axial profiles. The cadmium covered foil data are given in Table 6.2 and the cadmium ratios are tabulated in Table 6.3. The resulting radial and axial profiles are shown in Figures 6.5 and 6.6. The cadmium ratio at the center of the reactor was 15.2 compared to 22.3 for Configuration 1 and 9.4 for Configuration 2. The ratio at the outer edge of the fuel was 27.8 which agrees closely with that measured for Configuration 1 but is about 36% higher than the 17.8 measured for Configuration 2.

6.4 Resonance Detector Data - Gold Foils

6.4.1 Bare Gold Foil Data

All of the gold foil data obtained on assembly 3A are given in Table 6.4. The radial and axial distributions in the cavity from the bare gold foils normalized to the center of the core are shown in Figures 6.7 and 6.8. The peak at the outer edge of the fuel at the axial center dropped from 1.63 for Configuration 2 to 1.43. The same value for Configuration 1 was 1.13. The weighted average radial out to the edge of the fuel was 1.156 for this assembly compared to 1.063 and 1.244 for Configurations 1 and 2, respectively. The axial average was 1.058 as shown in Figure 6.8. This compares with 1.015 and 1.207 for Configurations 1 and 2, respectively.

The bare gold activation flux distribution in the end and radial reflector are shown in Figure 6.9. The gold data are power normalized as usual, to Run 1002 and these normalization data are given in Table 6.5. This power normalization gives a specific power-per-gram of U-235 at the core center of

$$\frac{66815 \times 79464 \times 123.2}{100000 \times 3.2 \times 10^{10}} = 2.04 \times 10^{-4} \text{ watts/gm U-235}$$

The total core power normalized to Run 1002 will include factors for the weighted radial average, the axial average and the total fuel in the reactor.

$$\begin{aligned} \text{Core power} &= 2.04 \times 10^{-4} \times 1.444 \times 1.065 \times 14.5 \times 10^3 \times \\ &0.932 = 4.24 \text{ watts} \end{aligned}$$

This configuration compares very closely to Configuration 2 in both end and radial reflectors. When normalized to the same core power, the radial reflector values were about 2% lower than Configuration 2. This is within the normal accuracy of this type of measurement. The most significant differences were in the points nearest the cavity wall. This,

however, is both a very sensitive area, where slight foil positioning errors would result in significant changes in foil activation as well as being the location most affected by changes in fuel loading. The fewer data points obtained with Configuration 3A than for Configuration 2 also results in less definition of the comparison near the cavity wall.

6.4.2 Cadmium Ratios - Gold Foils

The cadmium ratios obtained from the gold foils are given in Table 6.6. The cadmium ratios were again corrected to infinitely dilute foils. With reference to Configuration 1, the center of the cavity showed a 16% decrease in cadmium ratio, decreasing from 1.74 to 1.47. At the ends of the cavity through the radial center of the core, there was an inconsistency compared to Configuration 1. At the control rod end of the core the cadmium ratio was 1.82 for Configuration 1 and 2.46 for Configuration 3A, an unexpected 35% increase. At the separation plane, the change was from 1.84 to 1.66, a 10% decrease. The value at the control rod end of the cavity appears to have an anomalously low cadmium covered foil count. There was no measureable change in the cadmium ratio in the extreme corners of the cavity as the average value was 2.10 for this arrangement compared to an average of 2.06 for Configuration 1.

The cadmium ratios in the end and radial reflectors are presented graphically in Figure 6.10. There was virtually no change in the values from the radial reflector over Configuration 1. The points from the end reflector, however, decreased slightly compared to Configuration 1 and fall between the values from the two previously discussed configurations.

6.4.3 Thermal Neutron Flux Distribution - Gold Data

The thermal neutron flux distributions as determined from the gold foil data in the cavity and reflector regions are given in Table 6.6 and presented graphically in Figures 6.11 and 6.12. These data were compared to Configuration 1 as will be noted in the table. The center of the core shows a 52% flux reduction over Configuration 1. The radial reflector thermal flux showed an average decrease of about $15 \pm 2\%$ which was slightly lower than the $12 \pm 2\%$ for Configuration 2. This would tend to indicate some inconsistency in the data as an increase towards the values for Configuration 1 would be expected as the fuel radius was increased and the fuel density lowered. The differences, however, are within the experimental error.

The end reflector data appears to be consistent except for the point at zero cm which was too low compared to the other data points near this position. The same general flux shape was observed in the end reflector as noted for Configuration 2 except that the magnitude lies between that of Configuration 1 and Configuration 2.

TABLE 6.1

Critical Fuel Tray Loading Arrangement - Configuration 3A

Tray No.	Number of Surfaces	Fuel Sheets per Tray (1)	Fuel Weight (2) (gm)
1	2	22	57.6
2	8	88	230.6
3	10	110	288.2
4	12	132	345.8
5	14	154	403.5
6	14	154	403.5
7	16	176	461.1
8	16	176	461.1
9	18	198	518.8
10	18	198	518.8
11	18	198	518.8
12	20	220	576.4
13	20	220	576.4
14	20	220	576.4
15	20	220	576.4
16	20	220	576.4
17	20	220	576.4
18	20	220	576.4
19	20	220	576.4
20	20	220	576.4
21	20	220	576.4
22	20	220	576.4
23	18	198	518.8
24	18	198	518.8
25	18	198	518.8
26	16	176	461.1
27	16	176	461.1
28	14	154	403.5
29	12	132	345.8
30	12	132	345.8
31	8	88	230.6
32	6	66	172.9
Totals	504	5544	14525.4

(1) Equivalent 1.0 size fuel sheets.

(2) Weights are based on 2.62 grams per 1.0 size fuel sheet.

TABLE 6.2

Catcher Foil Data - Configuration 3A

Run 1017

Foil No.	Type	Location		Tray No.	Normalized Counts (l)	Ratio of Local to Core Center (Foil No. X)
		Radial (cm)	Axial (cm)			
1	Bare	0	212.0	17	89217	1.339
2	Bare	0	196.8	17	73400	1.102
3	Bare	0	181.5	17	66866	1.003
4	Bare	0	166.3	17	65492	0.983
5	Bare	0	151.1	17	66635	1.000 (X)
6	Bare	0	135.8	17	72028	1.081
7	Bare	0	120.6	17	67379	1.011
8	Bare	0	105.3	17	71431	1.072
9	Bare	0	90.1	17	95223	1.429
10	Bare	15.2	166.3	17	67336	1.011
11	Bare	15.2	151.1	17	--	--
12	Bare	15.2	135.8	17	73790	1.107
13	Bare	30.5	166.3	17	74767	1.122
14	Bare	30.5	151.1	17	72707	1.091
15	Bare	30.5	135.8	17	81384	1.221
16	Bare	45.7	166.3	17	90199	1.354
17	Bare	45.7	151.1	17	87584	1.314
18	Bare	45.7	135.8	17	95746	1.437
19	Bare	61.0	166.3	17	123897	1.859
20	Bare	61.0	151.1	17	126771	1.902
21	Bare	61.0	135.8	17	127422	1.912
22	Bare	76.2	166.3	17	134826	2.023
23	Bare	76.2	151.1	17	136783	2.053
24	Bare	76.2	135.8	17	136542	2.049
25	Bare	91.4	166.3	17	137024	2.056
26	Bare	91.4	151.1	17	135052	2.027
27	Bare	91.4	135.8	17	138586	2.080
28	Bare	10.2	212.0	17	91855	1.378
29	Bare	20.3	212.0	17	92750	1.392
30	Bare	30.5	212.0	17	94080	1.412
31	Bare	40.6	212.0	17	97083	1.457
32	Bare	Missing	212.0	17	--	--
33	Bare	61.0	212.0	17	115345	1.731
34	Bare	71.1	212.0	17	126494	1.898
35	Bare	81.3	212.0	17	135166	2.028
36	Bare	91.4	212.0	17	134136	2.013

TABLE 6.2
(Continued)

Run 1018

Foil No.	Type	Location		Tray No.	Normalized Counts (1)	Ratio of Local to Core Center (Foil No. X)
		Radial (cm)	Axial (cm)			
1	Bare	61.0	212.0	17	123916	1.880
2	Bare	61.0	196.8	17	114876	1.742
3	Bare	61.0	181.5	17	110425	1.675
4	Bare	61.0	166.3	17	110957	1.683
5	Bare	61.0	151.1	17	110924	1.683
6	Bare	61.0	135.8	17	112802	1.711
7	Bare	61.0	120.6	17	104283	1.582
8	Bare	61.0	105.3	17	117317	1.780
9	Bare	61.0	90.1	17	127552	1.935
10	Bare	0	151.1	17	65926	1.000 (X)
11	Bare	0	135.8	17	71574	1.086
12	Bare	0	120.6	17	68178	1.034
13	Bare	0	105.3	17	76012	1.153
14	Bare	0	90.1	17	95934	1.455
15	Bare	91.4	90.1	17	145692	2.210
16	Bare	91.4	212.0	17	131300	1.992
17	Cd	91.4	212.0	17	4485	
18	Cd	91.4	90.1	17	4392	
19	Cd	15.2	151.1	17	4158	
20	Cd	30.5	151.1	17	4380	

Run 1019

1	Bare	30.5	212.0	17	94550	1.393
2	Bare	30.5	196.8	17	77366	1.140
3	Bare	30.5	181.5	17	69036	1.017
4	Bare	30.5	166.3	17	68528	1.010
5	Bare	30.5	151.1	17	67881	1.000 (X)
6	Bare	30.5	135.8	17	77899	1.148
7	Bare	30.5	120.6	17	68360	1.007
8	Bare	30.5	105.3	17	70618	1.040
9	Bare	30.5	90.1	17	99493	1.466
10	Cd	61.0	151.1	17	4563	
11	Cd	0	151.1	17	4390	
12	Cd	91.4	151.1	17	4742	

Run 1020

1	Cd	0	212.0	17	4956	
2	Cd	0	181.5	17	4438	
3	Cd	0	151.1	17	4153	
4	Bare	0	135.8	17	72561	
5	Cd	0	120.6	17	4223	
6	Bare	0	105.3	17	77066	
7	Cd	0	90.1	17	4968	

(1) Normalization to 100,000 counts on decay corrector.

TABLE 6.3

Catcher Foil Cadmium Ratios - Configuration 3A

Run No.	Location		Tray No.	Normalized Bare Foil Activity	Normalized Cd Foil Activity	Cd Ratio Bare/Cd Activity
	Radial (cm)	Axial (cm)				
1017,1020	0	90.1	17	95223	4968	19.2
1017,1020	0	120.6	17	67379	4223	16.0
1017,1019	0	151.1	17	66635	4390	15.2
1017,1020	0	181.5	17	66866	4438	15.1
1017,1020	0	212.0	17	89217	4956	18.0
1018	15.2	151.1	17	69500 (1)	4158	16.7
1017,1018	30.5	151.1	17	72707	4380	16.6
1017,1019	61.0	151.1	17	126771	4563	27.8
1017,1019	91.4	151.1	17	135052	4742	28.5
1018,1018	91.4	90.1	17	145692	4392	33.2
1018,1018	91.4	212.0	17	131300	4485	29.2

(1) This value is estimated from radial curve of bare foil data.

TABLE 6.4
Gold Foil Data - Configuration 3A

Run 1017						
Foil No.	Type	Location Radial (cm)	Axial (cm)	Activity (CPM) (1)	Foil Wt. (gm)	Specific Activity d/m/gm $\times 10^{-5}$ (2)
1	Cd	93.7	151.1	1207	.0392	3.318
2	Cd	103.5	151.1	111	.0357	0.335
3	Cd	0	89.4	710	.0182	4.204
4	Cd	0	59.6	119	.0137	0.936
Run 1018						
1	Bare	0	212.0	1225	.0147	8.867
2	Bare	0	196.8	1384	.0212	6.947
3	Bare	0	181.5	1031	.0163	6.730
4	Bare	0	166.3	1072	.0169	6.750
5	Bare	0	151.1	1064	.0170	6.660
6	Bare	0	135.8	1414	.0213	7.064
7	Bare	0	120.6	1206	.0189	6.790
8	Bare	0	105.3	1376	.0200	7.321
9	Bare	0	90.1	1624	.0199	8.684
10	Bare	0	89.4	1519	.0161	10.039
11	Bare	0	74.9	3427	.0198	18.417
12	Bare	0	59.6	3150	.0216	15.518
13	Bare	0	44.4	2264	.0217	11.102
14	Bare	0	29.1	1123	.0169	7.071
15	Bare	0	13.9	625	.0195	3.410
16	Bare	0	0	77	.0178	0.460
17	Bare	14.0	151.1	966	.0148	6.945
18	Bare	29.2	151.1	1185	.0184	6.853
19	Bare	45.04	151.1	1345	.0187	7.653
20	Bare	61.0	151.1	1885	.0211	9.506
21	Bare	75.0	151.1	1865	.0193	10.282
22	Bare	91.4	151.1	1762	.0171	10.964
23	Bare	93.7	151.1	1929	.0163	12.592
24	Bare	108.2	151.1	2578	.0177	15.498
25	Bare	123.5	151.1	2449	.0221	11.791
26	Bare	138.7	151.1	1451	.0199	7.759
27	Bare	154.0	151.1	707	.0159	4.731
28	Bare	169.2	151.1	372	.0160	2.474
29	Bare	184.4	151.1	104	.0152	0.728
30	Bare	91.4	212.0	1638	.0177	9.847
31	Bare	91.4	90.1	1754	.0168	11.109
32	Cd	91.4	90.1	643	.0193	3.545
33	Cd	91.4	212.0	620	.0204	3.234

TABLE 6.4
(Continued)

Foil No.	Foil Type	Location		Activity (CPM) (1)	Foil Wt. (gm)	Specific Activity d/m/gm x 10 ⁻⁵ (2)
		Radial (cm)	Axial (cm)			
Run 1019						
1	Cd	0	212.0	682	.0190	3.856
2	Cd	0	181.5	608	.0187	3.492
3	Cd	0	82.5	827	.0202	4.398
4	Cd	0	67.2	328	.01935	1.821
5	Cd	100.6	151.1	518	.0153	3.637
6	Cd	115.9	151.1	163	.0172	1.018
Run 1020						
1	Cd	91.4	151.1	441	.0151	4.405
Run 1021						
1	Cd	0	151.1	2202	.0185	3.518
2	Cd	0	120.6	2246	.0186	3.569
3	Cd	0	90.1	1629	.0212	2.271
4	Cd	0	74.9	1830	.0162	3.339
5	Cd	0	44.4	81	.0164	0.146
6	Cd	30.5	151.1	2022	.0163	3.667
7	Cd	61.0	151.1	2377	.0182	3.860
8	Cd	108.2	151.1	1207	.0164	2.175
9	Cd	138.7	151.1	38	.0184	0.061

(1) Observed activity corrected to shutdown time.

(2) Specific activity is the disintegration per minute per gram at shutdown normalized for power to Run 1002.

TABLE 6.5
Power Normalization Factors - Configuration 3A

<u>Run</u>	<u>Time</u>	<u>Decay Time (min)</u>	<u>Decay Factor</u>	<u>Activity (CPM)</u>	<u>Corrected Activity (CPM) (1)</u>	<u>Norm Factor</u>
1017	1615.36	20.30	.40	312093	124837	0.638
	1616.50	21.44	.42	296434	124502	
	1617.83	22.77	.44	282542	124318	
					<u>124552</u>	
1018	1508.72	36.57	.70	179663	125764	0.630
	1509.94	37.79	.73	173118	126376	
	1511.16	39.01	.755	167203	126238	
					<u>126126</u>	
1019	1103.35	40.38	.78	159636	124516	0.636
	1104.57	41.60	.81	154426	125085	
	1105.83	42.86	.84	148880	125059	
					<u>124887</u>	
1020	1304.69	57.05	1.16	76599	88855	0.893
	1305.95	58.31	1.19	74389	88523	
	1307.17	59.53	1.23	72759	89494	
					<u>88957</u>	
1021	1527.29	44.16	0.86	522311	449187	0.175
	1528.56	45.43	0.89	511181	454951	
	1529.86	46.73	0.925	494563	457471	
					<u>453870</u>	

(1) Activity decay corrected to 50 min. after shutdown.

TABLE 6.6

Gold Foil Cadmium Ratios and Thermal Neutron Flux - Configuration 3A

Radial (cm)	Axial (cm)	d/m/gm $\times 10^{-5}$	d/m/gm $\times 10^{-5}$	Cd Ratio	Corrected Cd Ratio	Thermal Flux A(1)	B(2)
0	0	0.460	0.00095(3)	484.00	271.00	0.17	1.134
0	13.9	3.410	0.005 (3)	682.00	381.00	1.25	1.059
0	29.1	7.071	0.028 (3)	253.00	142.00	2.58	1.011
0	44.4	11.102	0.146	76.04	43.92	4.02	0.969
0	59.6	15.518	0.936	16.58	10.52	5.39	0.946
0	67.2	---	1.821	---	---	5.85	--
0	74.9	18.417	3.339	5.52	3.63	5.60	0.916
0	82.5	---	4.398	---	---	4.04	--
0	89.4	10.039	4.204	2.39	1.74	2.07	0.736
0	90.1	8.684	2.271	3.82	2.46	2.33	0.918
0	121.5	6.790	3.569	1.90	1.50	1.19	0.522
0	151.1	6.660	3.518	1.89	1.47	1.11	0.489
0	181.5	6.730	3.493	1.93	1.48	1.12	0.496
0	212.0	8.867	3.856	2.30	1.66	1.71	0.668
0	151.1	6.660	3.518	1.89	1.47	1.11	0.489
30.5	151.1	6.853	3.667	1.87	1.52	1.22	--
61.0	151.1	9.506	3.860	2.50	1.83	2.14	0.896
91.4	151.1	10.964	4.405	2.49	1.90	2.47	0.864
93.7	151.1	12.593	3.318	3.80	1.99	2.92	0.818
100.6	151.1	---	3.637	---	---	4.03	--
108.2	151.1	15.498	2.175	7.13	4.51	4.90	0.860
115.9	151.1	---	1.018	---	---	4.78	--
123.5	151.1	11.791	0.335	35.20	15.50	4.17	0.876
138.7	151.1	7.759	0.0610	127.00	70.31	2.82	0.862
154.0	151.1	4.731	0.0090 (3)	526.00	281.00	1.73	0.870
169.2	151.1	2.474	0.0013 (3)	1903.00	1015.00	0.91	0.867
184.4	151.1	0.728	0.0002 (3)	3640.00	1941.00	0.27	0.900
91.4	90.1	11.109	3.545	3.13	2.13	2.81	0.986
91.4	212.0	9.847	3.234	3.04	2.06	2.45	0.884

(1) Column A gives the thermal flux in $\text{n/cm}^2/\text{sec/watt} \times 10^{-6}$ for Configuration 3A.

(2) Column B is the ratio of thermal flux in Configuration 3A to Configuration 1.

(3) Extrapolated from other cadmium covered foil data.

Fig. 6.1 Fuel tray installation pattern and nomenclature - configuration 3A

(1) All distances are from separation plane and are in cm.

Fig. 6.2 Configuration 3A fuel loading arrangement

Fig. 6.3 Radial power distribution from bare catcher foils - configuration 3A

Fig. 6.4 Axial power distribution from bare catcher foils at core center and core edge - configuration 3A

Fig 6.5 Catcher foil cadmium ratio-radial profile at an axial position of 151.1 cm - configuration 3A

Fig. 6.6 Catcher foil cadmium ratio - axial profile at core center - configuration 3A

Fig. 6 7 Radial distribution of bare gold foil activity in cavity at an axial position of 151.1 cm - configuration 3A

Fig. 6.8 Axial distribution of bare gold foil activity in the cavity at the core center - configuration 3A

Fig. 6.9 Bare gold foil activity distribution in the reflector - configuration 3A

Fig. 6.10 Gold cadmium ratios in the radial and end reflectors - configuration 3A

Fig. 6.11 Thermal neutron flux distribution radially through axial center of core - configuration 3A

Fig. 6.12 Thermal neutron flux distribution axially through radial center of core - configuration 3A

7.0 CONFIGURATION 3B

This configuration differed from Configuration 3A only in the amount of fuel in the reactor and in the removal of the 30.5 cm diameter plug in the movable table. An increase in fuel loading was necessary to compensate for the loss in reactivity due to removing the plug. There was D_2O only in the reflector regions.

7.1 Plug Removal

Prior to removing the end plug, there were 5572.5 sheets of fuel in the reactor and excess reactivity was $0.1561\% \Delta k$. With the plug out and 141 sheets or 365.6 grams of fuel added to the reactor, k-excess was $0.0868\% \Delta k$ with all rods fully withdrawn. Fuel was added uniformly to the active core region with the total core loading as shown in Table 7.1. Refer to Sections 6.1 and 6.3.1 for details on core arrangement prior to the change to Configuration 3B. Fuel worth measurements following the change over gave values of $(2.19 \pm 0.13) \times 10^{-3} \% \Delta k / \text{gram}$ axially along the fuel boundary and $(1.22 \pm 0.15) \times 10^{-3} \% \Delta k / \text{gram}$ at the core center. The ratio of the core boundary to core center is 1.80. The same ratio for the radial power profile is 1.83. If it is assumed that the fuel worth varies as the bare catcher foil profile the core average fuel worth is $(1.68 \pm .168) \times 10^{-3} \% \Delta k / \text{gram}$ of fuel. The average fuel worth for Configurations 3A and 3B is $(1.720 \pm .241) \times 10^{-3} \% \Delta k / \text{gm}$. Based on this average value and the differences in k-excess, the following plug worth is calculated:

$$\begin{aligned} \text{Plug worth} &= 365.6 \times (1.720 \pm .241) \times 10^{-3} + (0.1561 - 0.0868) \\ &= 698 \pm .088 \% \Delta k \end{aligned}$$

The above core average fuel worth was obtained by assuming the fuel worth throughout the active core followed the power distribution results. Fuel worths from the outer edge and core center were both used in the calculations.

7.2 Material Worth Measurements

An aluminum plate was placed at several radial positions within the D_2O radial reflector tank to determine the reactivity effect of aluminum displacing D_2O . The aluminum plate was 30.5 cm square by 0.952 cm thick and weighed 2.835 kg. The following values were measured.

<u>Plate Position from Tank Wall (cm)</u>	<u>k-excess ($\% \Delta k$)</u>
Base - Al plate out of reactor	0.1879
0	0.1126
22.9	0.1258
45.7	0.1817
76.2	0.2034
Al plate at top of hatch (91 cm)	0.2058
0 (repeat)	0.1123
Base (repeat)	0.1857
Base (repeat)	0.1849
Al plate at top of hatch (repeat)	0.1852

It will be observed here that there was an obvious change between the first base and the time the plate was at the top of the hatch the first time. Yet the other base runs show very close agreement with an average k-excess of $0.1859 \pm 0.0012\% \Delta k$. To determine the change in reactivity versus plate position, the k-excess value of $0.2058\% \Delta k$, the plate at the top of the hatch, was used as the base. Using an Al volume of 1050 cm^3 , the following were obtained:

<u>Location from Cavity Wall (cm)</u>	<u>Worth per cm^3 of Al Replacing D_2O ($\% \Delta k / \text{cm}^3$)</u>
0	-8.88×10^{-5}
22.9	-7.62×10^{-5}
45.7	-2.30×10^{-5}
76.2	-0.23×10^{-5}

If the above standard error of $0.0012\% \Delta k$ is assumed to be valid for each k-excess measurement, then the error on the difference between two measurements would be $\pm 0.002\% \Delta k$. This results in an estimated error of the Al worth per cm^3 displacing D_2O of $\pm 0.19 \times 10^{-5} \% \Delta k / \text{cm}^3$.

The above values may be used to evaluate the worth of structural Al displacing heavy water within the D_2O tank.

Fuel worth measurements, other than those given in the previous section, were obtained when increasing k-excess for the moderator temperature coefficient of reactivity measurement which involved the addition of a large amount of fuel. Table 7.2 presents the results. The fuel weight should be accurate to 1%. Excess reactivity values are based on an average total rod worth of $-4.268 \pm 0.044\% \Delta k$. The total reactivity change is estimated to have a standard error of $\pm 0.04\% \Delta k$ which results in an average fuel worth of $(1.516 \pm 0.004) \times 10^{-3} \% \Delta k / \text{gram}$. This is consistent with the previously quoted average of $(1.681 \pm 0.168) \times 10^{-3} \% \Delta k / \text{gm}$, i. e., the fuel worth decreases as the fuel loading increases. The reactivity change to fractional fuel change ($\Delta k / k / \Delta m / m$) is equal to 0.23.

A sheet of stainless steel $91.5 \text{ cm} \times 122 \text{ cm} \times 0.0965 \text{ cm}$ thick, weighing 8.65 kg placed on the cavity wall reduced k-excess $1.381 \pm 0.020\% \Delta k$. A second sheet of the same size but weighing 8.4 kg was placed on top of the first sheet and its worth was $-1.245 \pm 0.035\% \Delta k$. A linear extrapolation of these values may be made over the entire radial surface of the cavity wall by multiplying the above values by 6.28. A 0.0965 cm thick sheet of stainless steel over the inner surface of the radial cavity wall (not including the ends of the cavity) would cause an estimated decrease in excess reactivity of $8.68 \pm 0.13\% \Delta k$. A 0.193 cm thick liner over the same surface, extrapolates to be worth $-16.50 \pm 0.25\% \Delta k$, and to $-29\% \Delta k$ over the entire cavity surface including the ends. The worth appears to vary linearly with thickness over the range measured (as is expected, since $\Sigma_a X = 0.05$).

7.3 Rod Worth Measurements

Several rod bumps were made while obtaining reactivity measurements. These are summarized in Table 7.5. The average worth of actuators 1 to 6 was $-4.26 \pm 0.044\% \Delta k$. A 5% standard error is not unusual when determining the total worth of such a large number of rods.

The rod worths for actuators 1, 1 and 2 and the first value for actuator 6 were unshadowed measurements, i.e., there were no other rods inserted into the reactor except the rods being measured. The measurement on actuator 7 was quite heavily shadowed as actuator 2, 4 and 5 were completely inserted and actuator 3 was at 3569 (approximately 36% withdrawn). Actuator 7 should be worth about the same as actuator 6 under identical shadowing conditions; but because of the shadowing, actuator 7 was about 16% lower in worth than the unshadowed worth of actuator 6. The second measured worth of actuator 6 of $-0.734\% \Delta k$ was obtained with actuators 4 and 5 inserted. These actuators are a significant distance from actuator 6 and thus had only a small effect on the worth of this actuator. Actuators 4 and 5 were also virtually unshadowed as only actuator 6 was inserted to 2206 (approximately 22% withdrawn) with all other rods withdrawn.

7.4 Reflector Temperature Coefficient of Reactivity

The reflector temperature coefficient of reactivity measurement was made at the end of Configuration 3B testing and, therefore, followed the power distribution measurements. To compensate for the expected loss in reactivity, k-excess was increased by uniformly adding fuel to the reactor. A total of 762 sheets of fuel representing about 2 kg was placed in the reactor and k-excess was $2.9\% \Delta k$. The exact loading is given in Table 7.4.

The reflector (D_2O) temperature coefficient of reactivity was measured for Configuration 3B from an average D_2O temperature of $31.7^\circ C$ to $70.2^\circ C$. The measurement was performed in several increments thus defining a curve of reactivity change versus temperature as shown in Figure 7.1. A summary of the measured data is presented in Table 7.5. It will be observed from these data that there was a difference in relative k-excess with the heaters on and heaters off although the average D_2O temperature was virtually unchanged. It was found that by waiting for about 30 minutes after all heaters were turned off that k-excess reached an equilibrium condition. The points shown on the curve represent the data obtained after waiting about 30 minutes from the time the heaters were turned off.

The relative k-excess values given in the table are based on actuators 3, 4 and 5 being fully inserted, actuator 6 was at 4308 digits on the ratiometer and actuator 2 varied in position from 1050 at the beginning of the measurements to 3000 at the conclusion of the test. These changes are noted in Table 7.5. This procedure allowed an evaluation of reactivity changes based on period differences only. No rod worths were required to evaluate the data, since it was assumed that the rod worth did not change over a small temperature range. Rod worths, however, were checked at several points during the course of

the measurements. There was no indication of rod worth change as can be seen from Table 7.3. There was considerable random variation in the measured worth of actuator 2, however, the worth of actuators 1 to 6, as a bank of rods, was constant and agreed with previous values obtained during the k-excess buildup for this temperature coefficient measurement.

As the D_2O temperature increased, the overflow was drained into barrels and weighed. A total of 288 kg from the fixed tank and 143 kg from the movable tank overflowed the reflector volume as a result of the $38.5^\circ C$ temperature rise from $31.7^\circ C$ to $70.2^\circ C$. Calculations, using the D_2O density data⁽⁵⁾ and taking into account the Al expansion, gave a change of 281.7 kg for the fixed tank and 138.3 kg for the movable tank over the above temperature change. The measured and calculated values are in very good agreement. Correction for Al expansion represented 20% of the above calculated values.

7.5 Power Distribution Measurements

Before power distribution measurements were made, 53.1 gm of fuel sheet (20 size 1.0 sheets) were added to trays 31 and 32 to increase k-excess slightly. All rods were withdrawn for power mapping except actuator 6 which was approximately 32 cm withdrawn. The D_2O temperature was nominally $27^\circ C$.

Only catcher foils were exposed in the active core for Configuration 3B, as little or no change was expected over Configuration 3A. Considerable detailed data had been obtained just prior to removing the plug (Configuration 3A), so only minimal foil measurements were made after the plug removal, except near the location of the newly created hole in the reflector.

The bare catcher foil data obtained on Configuration 3B are given in Table 7.6. The radial and axial power profiles are shown in Figures 7.2 and 7.3. The radial power was slightly lower than in Configuration 3A near the outer edge of the fueled region, which resulted in a lower weighted average of 1.310 compared to 1.444 prior to removing the plug. This represents a 9% decrease which is in the opposite direction from that which might be expected with a slight increase in fuel loading.

Compared to Configuration 3A, the longitudinal power profile showed an increase in power at both ends of the core with respect to the core center. The larger increase was noted at the end where the plug was removed. The change in relative distribution caused a 5.5% increase in the axial average over that in Configuration 3A.

Several catcher foils were placed across the void created by removing the 30.5 cm diameter plug. This measurement was made at the separation plane and the resulting curve is presented in Figure 7.4. There was a definite increase of about 10% in specific power from the edge to the center of the hole. Further comparisons were made by plotting the radial power distribution at the separation plane before and after removing the plug. This comparison is shown in Figure 7.5. The

increase in specific power over the void region is believed to be caused by the streaming of thermal flux from the peak flux region in the D_2O , occurring around 15 cm from the cavity wall. The perturbation over the remaining portion of the radius is quite likely due to the overall shifting of the thermal flux distribution radially within the D_2O due to removing the center plug. The fact that all data is normalized to the core-center specific power accounts for the overall shifting of the relative power at the separation plane, and results in this end of the core accepting a greater fraction of the overall total reactor power.

7.6 Resonance Detector Data - Indium Foils

7.6.1 Bare Indium Data

As stated in the previous section, a minimal amount of flux and specific power data was obtained on Configuration 3B because of its similarity to Configuration 3A. No gold foils were exposed, but instead indium foil activations were obtained with the 30.5 cm plug removed. Besides the indium data from the end and radial reflectors, an axial traverse at the radial center and a single point near the outer edge of the fuel at the separation plane were obtained. All of the indium data are contained in Table 7.7. Power normalization factors for these data are given in Table 7.8. The relative axial flux distribution from the indium is given in Figure 7.5. The data were normalized to 45.7 cm instead of 61 cm as there was no foil at the axial center. This point does not appear to be out of line with the other data. The individual points and the average of 1.069 may, therefore, be slightly lower than they would have been had they been normalized to the core center. The curve indicates only a one to two percent difference caused by the altering of the normalization point to 45.7 cm. Compared to the normalized gold data, the only noticeable change in relative axial flux between Configuration 3A and 3B was at the end of the reactor where the plug was removed. At this point the indium data show a somewhat lower value of 1.205 compared to 1.330 for gold.

The foil activity distribution in the reflectors obtained from the bare indium foils is presented in Figure 7.7. The gold and indium data were compared to see if the relative flux distribution was significantly different as indicated by the two types of foils and the two configurations. This comparison is shown in Table 7.9 and as will be observed, there was no measureable difference assuming a possible error of about 5%.

7.6.2 Cadmium Ratios - Indium Foil-

The cadmium ratios obtained from the indium foils are given in Table 7.10. The ratios were corrected to infinitely dilute foils as was done with the gold foil data. The cadmium ratios within the core are all higher than from gold on Configuration 3A. Within the reflectors, there was no significant difference. Figure 7.8 presents the ratios in the reflectors. Since these values are about the same as for gold, it would indicate that the spectrum is essentially flat in lethargy over the resonance energies for gold and indium from about 1 to 10 ev, i.e., the ratio of resonance integral to thermal cross section is the same for both isotopes, 2500 to 162 barns for the In 54 min activity vs. 1555 to 98 barns for the gold.

7.6.3 Thermal Flux Distribution - Indium Data

Thermal flux was calculated from the bare and cadmium covered indium foils using the procedure given in Section 4.4.3. The flux values obtained are given in Table 7.10 and Figures 7.9 and 7.10. It will be noted from Table 7.10 that, compared to the thermal flux obtained from gold, there was a higher flux per watt of power along the entire axial centerline in the cavity, by about 20%, while the end and radial reflectors showed a decrease of $10 \pm 3\%$.

After seeing these results, a check was made in comparable places in the cavity near the cavity wall where the flux was uniform to see if gold and indium would give the same thermal flux. Within a standard error of about 2%, the two types of foils gave the same flux. It was, therefore, concluded that the differences noted above were real. Removing the 30.5 cm plug enhanced the thermal flux around the void region and this apparently was propagated most of the way along the axial center of the cavity. Unfortunately, radial traverses were not made, but the point at the cavity wall supports the conclusions that the thermal fluxes near the outer radius of the cavity had to be proportionately lower (so that the total thermal core flux per unit power was nominally constant) since the two fuel loadings were virtually identical.

7.7 Neutron Lifetime Measurements

Neutron lifetime was measured by monitoring the decay from neutron pulses within the cavity reactor. The neutron source was a TMC Model 211 pulse neutron generator. Neutron population in the core was recorded on a 256 channel time of flight unit. A neutron sensitive chamber was placed at the axial center of the cavity on the inner surface of the cavity wall. The neutrons were emitted from the end of a 304.8 cm long drift tube on the generator which extended through the 30.5 cm hole in the movable end reflector. The end of the drift tube was essentially lined up with the separation plane.

The relationship used to determine lifetime from the observed decay (α) is as follows:

$$\alpha = \frac{\Delta k + k\beta}{\ell}$$

where:

α = the measured value of the characteristic prompt decay

k = the multiplication factor

Δk = the dollars subcritical

β = the effective delayed neutron fraction

ℓ = the neutron lifetime

For this reactor $\beta = 0.00765$.

All measurements were made with the reactor subcritical. This was accomplished by inserting control rods to the desired subcritical level.

A summary of the measured data is given in Table 7.11. The data were all fit by least squares to a single exponential decay plus a background. (A double exponential plus background gave no significant improvement in the fit.) The statistical errors of the fit parameters were also calculated. This error was used as a weighting factor when the results of numerous runs under the same subcritical conditions were used to obtain an average. The quoted errors are the results of the statistical errors calculated from the fitted parameters as indicated above.

The average neutron lifetime was $(3.10 \pm 0.05) \times 10^{-3}$ seconds. The values obtained at the various subcritical levels agreed very well with each other even though the values at 1.0 and 2.0% subcritical were from a single measurement. The data also show that better results are obtained with the lower pulsing rates.

It will also be noted from the table that the background component increased substantially as the reactor approached delayed critical. This was due to the decreasing slope or much slower decay. A typical curve showing this is given in Figure 7.11. This is for 2.0% Δk subcritical and shows only the smooth curves as determined from the computed curve fit. The high background was due primarily to the delayed neutrons coupled with the long neutron lifetime associated with the system and the subcritical level. Similar results from the most subcritical level is shown in Figure 7.12. It will be seen here that the background was not so severe principally because of the larger alpha or faster prompt decay.

It will also be noted from Table 7.11 that the slower pulsing rates and wider channel width gave less calculated error. Pulsing the reactor as many as 10 pulses per second did not allow sufficient time between pulses for the prompt component to undergo adequate decay (less than factor of e at two of the levels) and created larger errors on the fitted alphas than at the lower pulsing rates.

None of the so-called " $k\beta/\lambda$ " or "prompt/delayed area ratio" methods could be applied successfully with this reactor. For these methods to work, the following conditions are required:

1. Pulse repetition rate $\ll (\alpha - \frac{k\beta}{\lambda})$
2. Pulse repetition rate $\gg$ fastest delayed neutron precursor.

Neither condition could be met. The fastest delayed neutron precursor (3.01 sec^{-1}) is the same order of magnitude as the prompt neutron decay, except at extreme conditions of subcriticality.

TABLE 7.1

Critical Fuel Tray Loading Arrangements - Configuration 3B

Tray No.	Number of Surfaces	Fuel Sheets per Tray (1)	Fuel Weight (2) (gm)
1	2	26	68.1
2	8	88	230.6
3	10	115	301.3
4	12	135	353.7
5	14	161	421.8
6	14	154	403.5
7	16	184	482.1
8	16	187	489.9
9	18	207	542.3
10	18	198	518.8
11	18	207	542.3
12	20	223	584.3
13	20	230	602.6
14	20	220	576.4
15	20	230	602.6
16	20	223	584.3
17	20	230	602.6
18	20	220	576.4
19	20	230	602.6
20	20	223	584.3
21	20	230	602.6
22	20	220	576.4
23	18	207	542.3
24	18	201	526.6
25	18	215	563.3
26	16	177.5	465.0
27	16	184	482.1
28	14	154	403.5
29	12	138	361.6
30	12	135	353.7
31	8	92	241.0
32	6	69	180.8
Totals	504	5713.5	14969.4

(1) Number of equivalent size 1.0 fuel sheets

(2) Weights are based on 2.62 grams per size 1.0 fuel sheet

TABLE 7.2

Fuel Worth During Excess Reactivity Increase for Moderator Temperature Coefficient

Fuel Addition (grams)	Tray Location of Addition	k_{ex} Increase (% Δk)	Fuel Worth (% Δk /gm)
208.1	28, 29, 30, 31, 32	0.6227	2.988×10^{-3}
267 ⁽¹⁾	24, 25, 26, 27	0.3402	1.274×10^{-3}
311.1	20, 21, 22, 23	0.4054	1.303×10^{-3}
314 ⁽¹⁾	16, 17, 18, 19	0.3937	1.254×10^{-3}
457.4	10, 11, 12, 13, 14, 15	0.5931	1.297×10^{-3}
304.6	4, 5, 6, 7, 8, 9	0.4439	1.457×10^{-3}
75.0	1, 2, 3	0.1374	1.832×10^{-3}
Total 1937.5	Total	2.9364	Avg. 1.516×10^{-3}

(1) Fuel weights not obtained. Value given is an estimate based on the number of sheets added and 2.62 grams per sheet.

TABLE 7.3

Rod Worth Measurements - Configuration 3B

Actuator No.	Number of Rods	Temperature ($^{\circ}\text{C}$)	Actuator Worth % Δk
1	3	Ambient	-0.879
1 and 2	6	Ambient	-1.655
7	3	Ambient	-0.635
6	3	Ambient	-0.752
6	3	Ambient	-0.734
4 and 5	5	Ambient	-1.281
1 to 6	17	Ambient	-4.319
1 to 6	17	Ambient	-4.297
1 to 6	17	Ambient	-4.268
1 to 6	17	Ambient	-4.252
1 to 6	17	Ambient	-4.280
1 to 6	17	Ambient	-4.192
2	3	31.7	-0.813
2	3	32.9	-0.617
2	3	47.9	-0.834
2	3	56.9	-0.776
2	3	64.5	-0.762
1 to 6	17	64.4	-4.260
1 to 6	17	70.2	-4.341
1 to 6	17	70.0	-4.252

TABLE 7.4

Fuel Tray Loading for Reflector Temperature Coefficient Measurement
Configuration - 3B

Tray No.	Number of Surfaces	Fuel Sheets per Surface (1)	Fuel Weight (2) (gm)
1	2	28	73.4
2	8	104	272.5
3	10	125	327.5
4	12	159	416.6
5	14	201	526.6
6	14	182	476.8
7	16	200	524.0
8	16	203	531.9
9	18	225	589.5
10	18	234	613.1
11	18	225	589.5
12	20	263	689.1
13	20	250	655.0
14	20	260	681.2
15	20	250	655.0
16	20	263	689.1
17	20	250	655.0
18	20	260	681.2
19	20	250	655.0
20	20	263	689.1
21	20	250	655.0
22	20	260	681.2
23	18	225	589.5
24	18	237	620.9
25	18	233	610.5
26	16	209.5	548.9
27	16	200	524.0
28	14	182	476.8
29	12	150	393.0
30	12	159	416.6
31	8	109	285.6
32	6	86	225.3
Totals	504	6495.5	17018.4

(1) Equivalent size 1.0 fuel sheets

(2) Weights based on 2.62 grams per fuel sheet

TABLE 7.5

Moderator Temperature Coefficient of Reactivity - Configuration 3B

Run	Temperature °C		Wt. Avg.	Temp. Diff.	Relative kex	Δk_{ex}	$\Sigma \Delta k_{\text{ex}}$	$\% \Delta k / ^\circ \text{C}$	Heater Cond. ⁽⁴⁾
	Movable	Fixed							
116	31.4	31.8	31.7	--	.2236 ⁽¹⁾	--	--	--	off
118	32.5	33.3	32.9	1.2	.1714 ⁽¹⁾	-.0522	--	.0435	on
119	32.8	33.2	33.1	1.4	.2065 ⁽¹⁾	-.0171	--	.0122	off
120	34.3	35.0	34.8	3.1	.1789 ⁽¹⁾	-.0447	--	.0144	F off M on
120	34.8	35.0	34.9	3.2	.1882 ⁽¹⁾	-.0354	-.0354	.011	off
122	47.8	47.8	47.8	12.9	.1065 ⁽¹⁾	-.0817	--	.0063	F off M on
122	48.1	47.8	47.9	13.0	.1142 ⁽¹⁾	-.0740	--	.0057	off
122	48.1	47.8	47.9	13.0	.1194 ⁽¹⁾	-.0688	-.1042	.0053	off
123	57.5	57.3	57.4	9.5	.1802 ⁽²⁾	--	--	--	F off M on
124	57.2	56.8	56.9	9.0	.0357 ⁽¹⁾	-.0837	-.1879	.0093	off
124	57.1	56.8	56.9	9.0	.1977 ⁽²⁾	--	--	--	
125	64.6	64.4	64.5	7.6	.0429 ⁽²⁾	-.1548	--	.0203	on
125	64.6	64.4	64.5	7.6	.0616 ⁽²⁾	-.1361	-.3240	.0179	off
126	65.4	65.6	65.5	1.1	.2180 ⁽³⁾	--	--	--	off
127	65.4	65.6	65.5	1.1	.1800 ⁽³⁾	--	--	--	on
128	70.3	70.1	70.2	5.8	.0912 ⁽³⁾	-.1268	--	.0218	F off M on
130	70.3	70.0	70.1	5.7	.1022 ⁽³⁾	-.1178	-.4418	.0206	off

(1) Actuators 3, 4, 5 in, 1, 7 out, 6 at 4308, 2 at 1050

(2) Actuators 3, 4, 5 in, 1, 7 out, 6 at 4308, 2 at 1900

(3) Actuators 3, 4, 5 in, 1, 7 out, 6 at 4308, 2 at 3000

(4) In this column, "F" stands for fixed table heaters and "M" stands for movable table heaters.

TABLE 7.6

Catcher Foil Data - Configuration 3B

Run 1022 - Plug Out

Foil No.	Type	Location		Tray No.	Normalized Counts (1)	Ratio of Local to
		Radial (cm)	Axial (cm)			Core Center (Foil No. X)
1	Bare	0	212.0	17	155185 (2)	1.662
2	Bare	0	196.8	17	109333	1.171
3	Bare	0	181.5	17	95785	1.026
4	Bare	0	166.3	17	97135	1.041
5	Bare	0	151.1	17	93390	1.000 (X)
6	Bare	0	135.8	17	104442	1.119
7	Bare	0	120.6	17	99233	1.063
8	Bare	0	105.3	17	112272	1.203
9	Bare	0	90.1	17	144810	1.551
10	Bare	10.2	212.0	17	152222	1.631
11	Bare	20.3	212.0	17	134202	1.438
12	Bare	30.5	212.0	17	142811	1.530
13	Bare	40.6	212.0	17	155981	1.671
14	Bare	50.8	212.0	17	171022	1.832
15	Bare	61.0	212.0	17	190844	2.044
16	Bare	71.1	212.0	17	200875	2.152
17	Bare	81.3	212.0	17	199887	2.141
18	Bare	91.4	212.0	17	191789	2.054

Run 1023

1	Bare	0	212.0	17	101186	1.618
2	Bare	0	196.8	17	73841	1.181
3	Bare	0	181.5	17	63451	1.015
4	Bare	0	166.3	17	63889	1.022
5	Bare	0	151.1	17	62528	1.000 (X)
6	Bare	0	135.8	17	69524	1.112
7	Bare	0	120.6	17	67252	1.076
8	Bare	0	105.3	17	73883	1.182
9	Bare	0	90.1	17	93575	1.497
10	Bare	across gap 15.24	212.0		94246	1.508
11	Bare	12.70	212.0		99293	1.588
12	Bare	10.16	212.0		101639	1.625

TABLE 7.6
(Continued)

Run 1023 (Cont'd)						
Foil No.	Type	Location		Tray No.	Normalized Counts (1)	Ratio of Local to Core Center (Foil No. X)
		Radial (cm)	Axial (cm)			
		across gap				
13	Bare	7.62	212.0		104323	1.668
14	Bare	5.08	212.0		103676	1.658
15	Bare	2.54	212.0		104894	1.678
16	Bare	0	212.0		103447	1.654
17	Bare	2.54	212.0		105227	1.683
18	Bare	5.08	212.0		102606	1.641
19	Bare	7.63	212.0		103367	1.653
20	Bare	10.16	212.0		102394	1.638
21	Bare	12.70	212.0		99600	1.593
22	Bare	15.24	212.0		95315	1.524

Run 1031						
1	Bare	0	151.1	17	62056	1.000 (X)
2	Bare	15.2	151.1	17	65423	1.054
3	Bare	30.5	151.1	17	68102	1.097
4	Bare	45.7	151.1	17	77464	1.248
5	Bare	61.0	151.1	17	113610	1.831
6	Bare	76.2	151.1	17	129815	2.087

(1) Normalized to 100,000 counts on decay corrector.

(2) No normalizer foils were used on Run 1022. Foils counts are only relative.

TABLE 7.7

Indium Foil Data - Configuration 3B

Foil No.	Type	Location		Activity (CPM) (1)	Foil Wt. (gm) $\times 10^3$	Specific Activity
		Radial (cm)	Axial (cm)			d/m/gm $\times 10^{-6}$ (2)
Run 1022						
18	Bare	0	89.4	6335	5.10	145.00
17	Bare	0	74.9	16785	7.40	264.70
11	Bare	0	59.6	10954	5.84	219.00
14	Bare	0	44.4	8672	6.49	155.90
22	Bare	0	29.1	4237	5.16	95.90
19	Bare	0	13.9	2919	6.79	50.17
21	Bare	0	0	344	5.62	7.14
13	Cd	93.7	151.1	2861	5.12	65.22
16	Cd	138.7	151.1	46	5.15	1.04
Run 1023						
17	Bare	93.7	151.1	11021	7.40	173.50
22	Bare	108.2	151.1	10287	5.16	232.70
13	Bare	123.5	151.1	7723	5.12	175.70
15	Bare	138.7	151.1	5040	5.15	114.00
21	Bare	154.0	151.1	3329	5.62	68.99
19	Bare	169.2	151.1	2187	6.79	37.52
11	Bare	184.4	151.1	522	5.84	10.41
14	Cd	0	89.4	3453	6.49	61.97
18	Cd	0	44.4	118	5.10	2.70
Run 1024						
11	Cd	108.2	151.1	1649	5.84	42.50
20	Cd	154.0	151.1	7	5.19	0.20
15	Cd	0	74.9	2277	5.15	66.56
14	Cd	0	29.1	23	6.49	0.53
17	Bare	0	135.8	6556	7.40	133.40
21	Cd	0	166.3	2721	5.62	72.88
Run 1030						
12	Bare	0	90.1	6212	5.18	176.40
13	Bare	0	166.3	4699	5.12	135.00
18	Cd	0	135.7	2639	5.10	76.12
19	Cd	0	212.0	3153	6.79	68.32
22	Bare	0	181.5	4580	5.16	130.60

TABLE 7.7
(Continued)

Foil No.	Type	Location		Activity (CPM) (1)	Foil Wt. (gm) $\times 10^3$	Specific Activity
		Radial (cm)	Axial (cm)			d/m/gm $\times 10^{-6}$ (2)
Run 1031						
21	Cd	0	90.1	3059	5.62	81.05
15	Cd	0	181.5	2545	5.15	73.61
11	Bare	0	212.0	6302	5.84	160.70
Run 1032						
14	Cd	61.0	212.0	3149	6.49	72.82
20	Bare	61.0	212.0	6903	5.19	199.60

(1) Observed activity corrected to shutdown time.

(2) Specific activity is the disintegration per minute per gram at shutdown normalized for power to Run 1002.

TABLE 7.8

Power Normalization Factors - Configuration 3B

Run	Time	Decay Time (min)	Decay Factor	Activity (CPM)	Corrected Activity (CPM) (1)	Norm. Factor
1022	1525.71	26.21	0.50	186152	93076	0.514
	1527.03	27.53	0.52	177747	92428	
	1528.29	28.79	0.54	171005	92343	
No normalizers exposed on this run. Foils 1 to 7 from core used as normalizers. Normalization factor estimated from Run 1023.						
1023	1037.24	25.88	0.59	251805	148565	0.513
	1038.46	27.10	0.64	241006	154244	
	1039.68	28.32	0.70	231098	161769	
					<u>154859</u>	
1024	1524.78	26.69	0.50	240397	120198	0.663
	1526.23	28.14	0.525	228469	119946	
	1527.75	29.66	0.55	217279	119503	
					<u>119882</u>	
1030	1052.32	53.16	1.07	114693	122722	0.648
	1053.59	54.43	1.10	111282	122410	
	1054.80	55.66	1.13	108458	122558	
					<u>122563</u>	
1031	1321.94	33.52	0.63	191753	120804	0.656
	1323.10	34.68	0.66	183992	121435	
	1324.42	36.00	0.68	177975	121023	
					<u>121087</u>	
1032	1449.09	28.22	0.53	227925	120800	0.661
	1450.38	29.51	0.55	218575	120216	
	1451.59	30.72	0.57	209646	119498	
					<u>120171</u>	
1025	1527.50	35.23	0.67	185046	123981	0.640
	1528.75	36.48	0.70	178066	124646	
	1529.97	37.70	0.72	172013	123849	
					<u>124159</u>	

(1) Activity decay corrected to 50 min. after shutdown.

TABLE 7.5

Gold and Indium Foil Comparison in Reflector - Configurations 3A and 3B

Location		Normalized Activity	
Radial (cm)	Axial (cm)	Configuration 3A Au	Configuration 3B In
0	89.4	0.647	0.662
0	74.9	1.187	1.209
0	59.6	1.000	1.000
0	44.4	0.715	0.712
0	29.1	0.456	0.438
0	13.9	0.220	0.229
0	0	0.030	0.033
93.7	151.1	1.069	0.988
108.2	151.1	1.314	1.322
123.5	151.1	1.000	1.000
138.5	151.1	0.658	0.649
154.0	151.1	0.401	0.392
169.2	151.1	0.210	0.214
183.7	151.1	0.062	0.059

TABLE 7.10

Indium Foil Cadmium Ratios and Thermal Neutron Flux - Configuration 3B

Location		Bare	Cd	Cd	Corrected	Thermal Flux	
Radial	Axial	d/m/gm	d/m/gm	Ratio	Cd Ratio	A ⁽¹⁾	B ⁽²⁾
(cm)	(cm)	$\times 10^{-5}$	$\times 10^{-5}$				
0	0	7.143×10^6	2.300×10^4 (3)	311.00	215.00	0.162	0.953
0	13.9	5.017×10^7	1.140×10^5 (3)	440.00	311.00	1.14	0.912
0	29.1	1.009×10^8	5.616×10^5	180.00	119.43	2.17	0.841
0	44.4	1.641×10^8	2.837×10^6	57.80	41.22	3.50	0.871
0	74.9	2.786×10^8	7.006×10^7	3.98	3.17	4.66	0.832
0	89.4	1.526×10^8	6.523×10^7	2.34	1.84	1.80	0.870
0	90.1	1.857×10^8	8.552×10^7	2.18	1.80	2.14	0.918
0	135.8	1.404×10^8	8.013×10^7	1.75	1.60	1.475	-
0	166.4	1.421×10^8	7.672×10^7	1.85	1.57	1.38	-
0	181.5	1.357×10^8	7.748×10^7	1.78	1.55	1.30	1.161
0	212.0	1.692×10^8	7.192×10^7	2.35	1.86	2.04	1.193
93.7	151.1	1.826×10^8	6.865×10^7	2.66	2.24	2.61	0.894
108.2	151.1	2.445×10^8	4.474×10^7	5.46	4.03	4.31	0.890
138.7	151.1	1.200×10^8	1.097×10^6	109.00	77.40	2.58	0.915
154.0	151.1	7.262×10^7	2.138×10^5	340.00	239.40	1.57	0.908
169.2	151.1	3.752×10^7	3.300×10^4 (3)	1137.00	796.00	0.856	0.941
184.4	151.1	1.041×10^7	5.400×10^3 (3)	1928.00	1350.00	0.237	0.878
61	212.0	2.101×10^8	7.665×10^7	2.74	2.11	2.79	-

(1) Column A gives the thermal flux in $n/cm^2/sec/watt \times 10^{-6}$ for Configuration 3B.

(2) Column B is the ratio of thermal flux in Configuration 3B to Configuration 3A.

(3) Extrapolated value from other cadmium covered foil data.

TABLE 7.11

Neutron Lifetime Measurements - Configuration 3B

Run No.	Channel Width (m sec)	Pulse Rate (sec ⁻¹)	Subcritical Level (% Δk)	Bkg. (CPM)	Intercept (CPM)	Alpha (sec ⁻¹)	± Error on Alpha (sec ⁻¹)
3-4	5.12	0.67	4.2±0.2	367	1294	-13.99	0.19
3-5	1.28	2.0	4.2±0.2	542	1879	-16.68	0.16
3-6	0.32	10.0	4.2±0.2	393	1165	-13.89	1.00
3-7	0.32	10.0	4.2±0.2	351	1004	-17.65	0.99
3-11	0.32	10.0	4.2±0.2	621	542	-15.62	1.75
3-15	1.28	2.0	4.2±0.2	1057	1130	<u>-13.86</u>	0.22
						-15.30±0.11 (1)	
3-16	1.28	2.0	2.0±.04	2162	447	-8.84	0.53
3-17	1.28	2.0	1.0±.02	1306	116	-5.75	1.01

5.49 \$ (4.2% Subcritical)

$$\ell = \frac{(.00765 \times 5.49 \times .958) + (.00765 \times .958)}{15.30 \pm 0.11} = 3.10 \pm .16$$

2.61 \$ (2.0% Subcritical)

$$\ell = \frac{(.00765 \times 2.61 \times .98) + (.00765 \times .98)}{8.84 \pm 0.53} = 3.07 \pm .19$$

1.31 \$ (1.0% Subcritical)

$$\ell = \frac{(.00765 \times 1.31 \times .99) + (.00765 \times .99)}{5.75 \pm 1.01} = 3.04 \pm .53$$

Weighted Average 3.10 ± 0.05

(1) All errors for results at a given subcritical level are assumed to be purely statistical counting uncertainties.

Fig. 7.1 Reflector temperature coefficient and reactivity - configuration 3B

Fig. 7.2 Radial power profile from bare catcher foils at an axial position of 151.1 cm - configuration 3B

Fig. 7.3 Axial power profile from bare catcher foils at core center - configuration 3B

Fig. 7.4 Power distribution across reflector void at separation plane from bare catcher foils - configuration 3B

Fig. 7.5 Effects on radial power at separation plane due to removing (30.5 cm) diameter plug - bare catcher foil data

Fig. 7.6 Axial distribution of bare indium foil activity in the cavity at core center

Fig. 7.7 Bare indium foil activity distribution in the reflector - configuration 3B

Fig 7.8 Cadmium ratio vs. distance from the radial and end reflectors - comparison of 3B

Fig. 7.9 Thermal neutron flux distribution radially through axial center of core - configuration 3B

Fig. 7.10 Thermal neutron flux distribution axially through radial center of core - configuration 3B

Fig. 7.11 Typical results from reactor lifetime measurements - reactor at 2.61 dollars subcritical

Fig. 7.12 Pulse neutron generator - exponential decay results - reactor at 5.49 dollars subcritical

8.0 CONFIGURATION 9 - SIMULATED INJECTOR TUBE

The purpose of this experiment was to simulate a fuel injector tube and determine the power generated in this tube with various types of neutron poison materials surrounding the tube. In order to simulate the tube, a 5.08 cm diameter aluminum tube was welded in the center of the 30.5 cm diameter tank which fit into the center of the movable reflector tank. Fuel and poison materials were then wrapped around another smaller aluminum tube with a length of 91.4 cm, a diameter of 3.81 cm, and a wall thickness of 0.1016 cm. The smaller tube containing fuel and poison was inserted into the 5.08 cm diameter tube to mockup the injection tube.

8.1 Injector Tube Loading and Reactivity Worth

As was mentioned earlier in this report, the standard size fuel sheets were 7.30 cm square by 0.00254 cm thick. The fuel was loaded on the 3.81 cm diameter tube in 12 axial stages. Each stage contained 21 layers of fuel. A total of 1209 grams was placed in the nozzle, causing k-excess to increase $0.809 \pm 0.054\% \Delta k$.

The critical position was all rods withdrawn except actuators 5 and 6 which were 18.3 and 7.7 cm withdrawn, respectively. The core fuel loading was the same as during power mapping of Configuration 3B except tray 5 (161 fuel sheets) was removed to reduce k-excess. Excess reactivity after installation of the simulated injector tube and removal of tray 5 was $0.870\% \Delta k$. The fuel loading within the cavity consisted of 5572.2 equivalent size 1.0 fuel sheets or 14.60 kg based on 2.62 gm per fuel sheet.

During this injector tube test series, several rod worth measurements were obtained. An average of nine measurements on actuator 1 gave a value of $-0.932 \pm 0.054\% \Delta k$. A single worth measurement on actuator 4 gave a worth of $-0.605\% \Delta k$. Eight separate measurements on actuator 6 produced an average of $-0.722 \pm 0.033\% \Delta k$. The average values were used where needed to evaluate changes in reactivity.

8.2 Unpoisoned Arrangement

The first configuration to be power mapped was with no poison material in the injector tube. Only bare catcher foil measurements were obtained as the value desired from the experiment was power generated in the nozzle compared to core power. A single radial and axial power distribution at the inner and outer surfaces of the fuel were obtained from the nozzle. In addition, an axial at the radial center of the core and a radial at the separation plane were measured. The data are given in Table 8.1. All of the foils are normalized to the center of the core. The position of the control rods during this measurement was all rods withdrawn except actuators 5 and 6 which were 34.2 and 0.0 cm withdrawn, respectively. Average D₂O temperature was 27°C.

The results are presented graphically in Figures 8.1 to 8.4. The radial average of 0.601 in the simulated injector tube was a straight average. No radial weighting factors were applied because the fuel was lumped on the outside of the aluminum tube over a very small annulus of

from 0.06 to 0.09 cm. The axial average at the outer edge of the fuel was 1.125 and at the inner surface of the fuel the average was 0.301. This gives an average ratio of the outside to the center of the fuel of 3.74. At the point where the radial was obtained this same ratio was 3.88.

The principle objective of this experiment was to determine the amount of power generated in the fuel injector tube. The average relative power in the tube is equal to the product of the average radial and the average axial at the outer surface of the fuel divided by the relative power at 35.6 cm on the outer surface of the fuel. This is as follows:

$$(0.601 \times 1.125) / 1.554 = 0.435$$

This is the average relative power-per-gram of fuel in the injector tube with respect to one watt-per-gram of fuel at the center of the core.

To determine the total relative power in the nozzle to the total relative power in the core, it is necessary to factor in the amount of fuel in the two regions and include the radial and axial averages for the core as follows:

1. Injector tube relative power is $0.435 \times 1.209 \times 10^3 = 0.5259 \times 10^3$
2. Core relative power is $1.310^* \times 1.128 \times 14.60 \times 10^3 = 2.157 \times 10^4$
3. Injector tube to core power ratio is $0.5259 \times 10^3 / 2.157 \times 10^4 = 0.0244$.

Figure 8.3 contains a comparison of the radial power profile between Configuration 9 and Configuration 3A at the end of the core containing the plug and injector tube simulation. The injector tube caused a general increase in power over this entire end of the reactor except at the axial centerline where there was a significant decrease in relative power. This point of power decrease was caused by the high thermal neutron absorption in the fuel in the nozzle region. The increase in the remaining portion of the radial profile along the end reflector appears to be due to the additional source in the end reflector caused by the fueled injector tube.

The axial power profile at the radial center of the core experienced a slight change as compared to Figure 6.4. The peak at the control rod end of the reactor increased from 1.45 to 1.59 and decreased at the separation plane from 1.37 to 1.31. The integrated average increased from 1.065 to 1.128, a 5.9% change.

8.3 Cadmium Lined Fuel Injector Tube

The addition of 0.0508 cm of cadmium around the nozzle caused k-excess to decrease from $1.775 \pm 0.049\% \Delta k$ to $0.177 \pm 0.007\% \Delta k$ for a

* This value is from Figure 7.2 for Configuration 3B.

total worth of the cadmium shield of $-1.598 \pm 0.050\% \Delta k$ and a net worth for the shielded injector tube with fuel of $-(0.79 \pm 0.07)\% \Delta k$. The cadmium was 12.37 cm x 91.4 cm by 0.0508 cm thick. This gives a calculated volume of 57.46 cm^3 of cadmium for a total weight of 497 grams.

Tray 5 was placed back in the reactor after cadmium had been added to the injector tube and 40 additional sheets were placed on Tray 5. This gave a total fuel loading within the cavity of 5773.5 equivalent size 1.0 sheets or 15.13 kg based on 2.62 grams per fuel sheet.

A single power distribution run was made with bare catcher foils in the tube and core. All rods were withdrawn during this run except actuator 6 which was 16.4 cm withdrawn. Average D_2O temperature was 27°C . The results are given in Table 8.2 and Figures 8.5 to 8.7. As will be noted, the cadmium reduced the power in the nozzle to a very low level. The end of the tube nearest the cavity sees the low energy neutrons scattering into the nozzle from the cavity as shown in Figure 8.5. The inner surface of the fuel at the end nearest the cavity showed a higher power level than the outer surface of the fuel because the outer surface of fuel was directly against the cadmium blanket. Between 5 and 10 cm from the cavity, the inner and outer fuel surfaces have essentially the same specific power and continue this way the rest of the distance along the tube as observed from Figure 8.5.

The power-per-gram of fuel in the nozzle with respect to a watt-per-gram of fuel in the center of the core was approximately 0.0216 which was the axial average on the outer surface of the fuel. The inner surface axial average was 0.0246. With the fuel evenly dispersed through the tube, as would be the case with gaseous fuel, this average would probably be slightly higher than measured here with the fuel lumped on the 3.81 cm diameter tube.

Again based on the average on the outer surface of fuel in the nozzle, the ratio of the total relative power in the injector to that in the cavity was as follows:

$$\frac{0.022 \times 1.209 \times 10^3}{1.310 \times 1.106 \times 15.13 \times 10^3} = \frac{26.60}{21.92 \times 10^3} = 1.21 \times 10^{-3}$$

The denominator contains the radial average, axial average and grams of fuel, respectively, for the cavity.

The radial power profile at the separation plane of the cavity (Figure 8.6) showed the same general curve shape as for the previous unpoisoned tube configuration but was slightly lower along the entire length of the curve. The weighted average was 5.1% lower with the cadmium than with no poison around the nozzle.

The axial power distribution shown in Figure 8.7 reflects the effect of the cadmium in the injector tube. The point next to the tube decreased from 1.31 before adding the cadmium to 1.12 with the cadmium. The average axial power decreased from 1.128 to 1.106, a 2.0% change.

The 0.0508 cm blanket of cadmium was removed and replaced with 0.0254 cm thick cadmium. This cadmium reduced k-excess from $1.574 \pm 0.059\% \Delta k$ (unpoisoned) to $0.221 \pm 0.013\% \Delta k$ for a total worth for the cadmium of $-1.353 \pm 0.061\% \Delta k$, and a net worth for the injector tube of $-(0.54 \pm 0.08)\% \Delta k$.

With 0.0254 cm of cadmium around the injector tube, the cavity was loaded as per the power distribution measurements for injector nozzle with 0.0508 cm of cadmium around it except 14 size 1.0 sheets were removed from tray 5 and 26 sheets of fuel were removed from tray 1. This left a total cavity loading of 5733.5 equivalent size 1.0 fuel sheets or 15.02 kg based on 2.62 gm per fuel sheet.

Power distribution measurements were made as with the other Configuration 9 arrangements and the results are presented in Table 8.3 and Figures 8.8 and 8.10. All rods were withdrawn except actuator 1 which was 31.4 cm withdrawn. Average D_2O temperature was $28^\circ C$. The radial power distribution measurement in the cavity at the separation plane was not obtained. The axial power profile in the nozzle showed a crossover between zero and 5 cm from the cavity for the data from the inside and outside of the fuel annulus. As with the 0.0508 cm cadmium cover, the power on the inner surface was higher than the outer surface of fuel at the separation plane. This was due again to the proximity of the cadmium at the outer surface of fuel and streaming of neutrons from the cavity into the injector tube region.

The radial power distribution in the tube at 35.6 cm from the cavity, shown in Figure 8.9, shows data scatter due primarily to the low counting rates from the foils. There was, however, a definite radial power gradient which was not observed with 0.0508 cm of cadmium around the injector. The 0.0254 cm of cadmium transmitted a very small but measureable thermal flux, whereas the 0.0508 cm of cadmium transmitted virtually none.

The power in the tube with respect to a watt of power at the center of the core was as follows:

$$(0.0364 \times 0.0177) / 0.027 = 0.0239$$

This is only 9% above the 0.0508 cm cadmium cover. The ratio of the total relative power in the nozzle to the total relative power in the cavity was:

$$\frac{0.024 \times 1.209 \times 10^3}{1.310 \times 1.086 \times 15.02 \times 10^3} = \frac{29.02}{21.37 \times 10^3} = 1.36 \times 10^{-3}$$

The above calculation contains similar factors to those used in previous calculations of this type. The axial average was taken from Figure 8.10. This curve average was 1.8% lower than with 0.0508 cm of cadmium around the nozzle which was within experimental error.

8.4 Borated Stainless Steel Line Injector Tube

Twelve layers of borated 304-type stainless steel were placed around the simulated injector tube. The material was 0.0127 cm thick per layer making a total of 0.1524 cm. The total weight of borated stainless steel was 1584 gm of which 0.7% was natural boron.

Placing this borated stainless steel around the injector tube caused k -excess to decrease $0.973 \pm 0.077\% \Delta k$ which was slightly more than the increase caused by the fuel in the nozzle, giving a net worth for this tube of $-(0.16 \pm 0.09)\% \Delta k$.

Power distribution data from catcher foils were obtained as usual and the results are shown in Table 8.4 and Figures 8.11 to 8.13. All rods were withdrawn except actuator 6 which was 32.2 cm withdrawn. Average D_2O temperature was $28^\circ C$. It will be noted from Figure 8.11 that three points lie above the curve. These are due to slight gaps in the poison material surrounding the nozzle. The borated stainless steel was in 14.0 cm wide strips and the high points are at or near these gaps where the strips join. There was no cross over at the cavity interface as with the cadmium poisons. There was, however, a significant increase in the power on the inner surface of fuel at this point as noted from this figure. The axial average was 0.359 at the outer edge of the fuel. The radial average, as shown in Figure 8.12, was 0.242 and the relative power at the outer surface of the fuel at 35.6 cm from the cavity was 0.449. These values give an average power-per-gram of fuel in the injector tube with respect to a watt-per-gram of fuel at the core center of 0.193.

The comparison of total relative power in the nozzle to the cavity gives a ratio of 1.07×10^{-2} as shown below.

$$(0.193 \times 1.209 \times 10^3) / (1.310 \times 1.113 \times 15.02 \times 10^3) = 1.07 \times 10^{-2}$$

The fuel loading in the cavity was the same as with 0.0254 cm of cadmium in the nozzle. The axial power profile in the cavity was essentially the same as for the previous arrangement. The average of 1.113 compares very well with 1.086 for 0.0254 cm of cadmium around the injector tube and 1.106 for 0.0508 cm of cadmium around the same tube.

TABLE 8.1

Catcher Foil Data - Configuration 9 - Unpoisoned

Run 1025

Foil No.	Location		Tray No.	Normalized Counts (l)	Ratio of Local to Core Center (Foil No. X)
	Radial (cm)	Axial (cm)			
36	0	212.0	17	78671	1.311
37	0	196.8	17	69748	1.163
38	0	181.5	17	65194	1.087
39	0	166.3	17	61024	1.017
40	0	151.1	17	59989	1.000 (X)
41	0	135.8	17	45206	0.754
42	0	120.6	17	63852	1.064
43	0	105.3	17	74793	1.247
44	0	90.1	17	95527	1.592
46	0	212.0	17	55219	0.920
47	7.62	212.0	17	86023	1.434
48	15.24	212.0	17	97743	1.629
49	22.86	212.0	17	97949	1.633
50	30.48	212.0	17	103044	1.718
51	45.72	212.0	17	114244	1.904
52	60.96	212.0	17	128969	2.150
45	76.20	212.0	17	136789	2.280
24	91.44	212.0	17	129804	2.164
(on injection tube)					
1	4	35.6		20919	0.349
2	6	35.6		22337	0.372
3	8	35.6		27692	0.462
4	10	35.6		29230	0.487
5	12	35.6		28763	0.479
6	14	35.6		36757	0.613
7	16	35.6		38468	0.641
8	18	35.6		64870	1.081
inside injection tube					
9		212.0		34309	0.572
10		217.0		28105	0.468
11		224.1		28590	0.477
12		232.0		28517	0.475
13		239.1		27488	0.458
14		247.1		24084	0.401

TABLE 8 1
(Continued)

Foil No.	Location		Tray No.	Normalized Counts (1)	Ratio of Local to Core Center (Foil No. X)
	Radial (cm)	Axial (cm)			
15		255.18		20377	0.340
16		262.80		17341	0.289
17		270.42		13760	0.229
18		278.04		10666	0.178
19		285.66		7645	0.127
20		293.28		4950	0.083
21		300.90		2166	0.036
	outside injection tube				
22		212.00		61052	1.018
23		217.08		73721	1.229
25		224.70		98219	1.637
26		232.32		100080	1.668
27		239.94		102105	1.702
28		242.56		93200	1.554
29		255.18		83550	1.393
30		262.80		66875	1.115
31		270.42		62138	1.036
32		278.04		44998	0.750
33		285.66		33043	0.551
34		293.28		20268	0.338
35		300.90		8458	0.141

(1) Normalized to 100,000 counts on decay corrector.

TABLE 8.2

Catcher Foil Data - Configuration 9 .0508 cm Cd

Run 1026 -

Foil No.	Location		Normalized Counts (I)	Ratio of Local to Core Center (Foil No. X)
	Radial (cm)	Axial (cm)		
32	0	212.0	68750	1.118
33	0	196.8	69384	1.129
34	0	181.5	63016	1.025
35	0	166.3	64009	1.041
36	0	141.1	61475	1.0
37	0	135.8	69380	1.129
38	0	120.6	65184	1.060
39	0	105.3	74333	1.209
40	0	90.1	96451	1.569
44	0	212.0	41880	.681
45	7.62	212.0	80239	1.305
46	15.24	212.0	90514	1.472
47	22.86	212.0	93351	1.518
48	30.48	212.0	100165	1.629
49	45.72	212.0	112389	1.828
50	60.96	212.0	121040	1.969
51	76.20	212.0	137433	2.235
52	91.44	212.0	122967	2.000
Layers of Fuel (On Injection Tube)				
1	4	35.6	594	.010
2	6	35.6	600	.010
3	8	35.6	583	.009
4	10	35.6	615	.010
5	12	35.6	569	.009
6	14	35.6	638	.010
7	16	35.6	604	.010
8	18	35.6	643	.010
Inside Injection Tube				
9		212.0	19921	.324
10		217.08	5368	.087
11		224.70	3322	.054
12		232.32	2069	.034
13		239.94	1077	.018
14		247.56	565	.009

TABLE 8.2
(Continued)Run 1026 (continued)

Foil No.	Location		Normalized Counts (l)	Ratio of Local to Core Center (Foil No. X)
	Radial (cm)	Axial (cm)		
Inside Injection Tube				
15		255.18	282	.005
16		262.80	160	.003
17		270.42	107	.002
18		278.04	112	.002
19		285.66	74	.001
20		293.28	58	.001
21		300.90	102	.002
22	Outside Injection Tube	212.0	13240	.215
23		217.08	4973	.081
24		224.70	3455	.056
25		232.32	2297	.037
26		239.94	1141	.019
27		247.56	593	.010
28		255.18	322	.005
29		262.80	167	.003
30		270.42	142	.002
31		278.04	88	.001
41		285.66	75	.001
42		293.28	79	.001
43		300.90	134	.002

(1) Normalized to 100,000 counts on decay corrector.

TABLE 8.3

Catcher Foil Data - Configuration 9 - .0254 cm Cd

Run 1028 -

Foil No.	Location		Normalized Counts (1)	Ratio of Local to Core Center (Foil No. X)
	Radial (cm)	Axial (cm)		
35	0	212.0	74817	1.181
36	0	196.8	67716	1.069
37	0	181.5	64104	1.012
38	0	166.3	63325	1.000 (X)
39	0	151.1	63331	1.000 (X)
40	0	135.8	70442	1.112
41	0	120.6	67437	1.065
42	0	105.3	75000	1.184
43	0	90.1	94954	1.500
Layers of Fuel (On Injection Tube)				
1	4	35.6	980	.015
2	6	35.6	986	.016
3	8	35.6	919	.015
4	10	35.6	1225	.020
5	12	35.6	1089	.017
6	14	35.6	1103	.017
7	16	35.6	1349	.021
8	18	35.6	1373	.022
Inside Injection Tube				
22		212.0	22411	.354
23		217.08	6187	.098
24		224.70	4075	.064
25		232.32	2828	.045
26		239.94	1634	.026
27		247.56	1067	.017
28		255.18	640	.010
29		262.80	441	.007
30		270.42	311	.005
31		278.04	156	.002
32		285.66	121	.002
33		293.28	76	.001
34		300.90	48	.001

TABLE 8.3
(Continued)

Run 1028 (continued)				
Foil No.	Location Radial (cm)	Axial (cm)	Normalized Counts (1)	Ratio of Local to Core Center (Foil No. X)
<hr/>				
9	Outside Injection Tube		13481	.213
10		212.0	6160	.097
11		217.08	5162	.082
12		224.70	4110	.065
13		232.32	2737	.043
14		239.94	1693	.027
15		247.56	1259	.020
16		255.18	962	.015
17		262.80	741	.012
18		270.42	425	.007
19		278.04	235	.004
20		285.66	142	.002
21		293.28	65	.001
		300.90		

(1) Normalization to 100,000 counts on decay corrector.

TABLE 8.4

Catcher Foil Data - Configuration 9 - .1524 cm Borated

Stainless Steel

Run 1027

Foil No.	Location Radial (cm)	Axial (cm)	Normalized Counts (l)	Ratio of Local to Core Center (Foil No. X)
36	0	212.0	78012	1.253
37	0	196.8	72393	1.163
38	0	181.5	63583	1.022
39	0	166.3	63623	1.022
40	0	151.1	62236	1.000 (X)
41	0	135.7	67740	1.109
42	0	120.6	65067	1.065
43	0	105.3	74440	1.219
44	0	90.1	92313	1.512
Layers of Fuel (On Injection Tube)				
1	4	35.6	10800	.177
2	6	35.6	10752	.176
3	8	35.6	11218	.184
4	10	35.6	12801	.210
5	12	35.6	13106	.215
6	14	35.6	16125	.264
7	16	35.6	16338	.267
8	18	35.6	20709	.339
Inside Injection Tube				
22		212.0	27079	.443
23		217.08	15101	.247
24		224.70	16292	.267
25		232.32	15120	.248
26		239.94	13796	.226
27		247.56	12509	.205
28		255.18	9089	.149
29		262.80	7561	.124
30		270.42	6180	.101
31		278.04	4640	.076
32		285.66	3293	.054
33		293.28	1950	.032
34		300.90	961	.016

TABLE 8.4
(Continued)

Run 1027 (continued)

Foil No.	Location Radial (cm)	Axial (cm)	Normalized Counts (1)	Ratio of Local to Core Center (Foil No. X)
9	Outside Injection Tube	212.0	30574	.501
10		217.08	31841	.521
11		224.70	37324	.611
12		232.32	36896	.604
13		239.94	38868	.636
14		247.56	27444	.449
15		255.18	26528	.434
16		262.80	19935	.326
17		270.42	18667	.306
18		278.04	12895	.211
19		285.66	8505	.139
20		293.28	5308	.087
21		300.90	2414	.040

(1) Normalization to 100,000 counts on decay corrector.

Fig. 8.1 Radial power distribution from bare catcher foils in injection tube - configuration 9 - unpoisoned

Fig. 8.2 Axial power distribution from bare catcher foils in injection tube - configuration 9 - unpoisoned

Fig. 8.3 Radial power distribution at separation plane from bare catcher foils - configuration 9

Fig. 8.4 Axial power distribution from bare catcher foils at center of core - configuration 9 - unpoisoned

Fig. 8.5 Axial power distribution from bare catcher foils in injection tube - configuration 9 with .0508 cm Cd

Fig 8 6 Radial power distribution at separation plane from bare catcher foils - configuration 9 with .0508 cm Cd

Fig. 8.7 Axial power distribution from bare catcher foils at center of core - configuration 9 with .0508 cm Cd

Fig 8.8 Axial power distribution from bare catcher foils in injection tube configuration 9 with 0254 cm Cd

Fig. 8.9 Radial power distribution from bare center-toke injection tube configuration 2 with 0.27 and 0.4

Fig. 8.10 Axial power distribution from bare catcher foils at center of core - configuration 9 with .0254 cm Cd

Fig. 8.11 Axial power distribution from bare catcher foils in injection tube - configuration 9 with .1524 cm borated stainless steel

Fig. 8.12 Radial power distribution from bare catcher foils in injection tubes configuration 9 with .1524 cm bored stainless steel

Fig. 8.13 Axial power distribution from bare catcher foils at center of core - configuration 9 with .1524 cm borated stainless steel

9.0 CONFIGURATION 10 - SIMULATED EXHAUST NOZZLE

The purpose of this experiment was to mockup an exhaust nozzle. Removal of the 30.5 cm diameter plug in the center of the movable end reflector, accompanied by the dispersal of fuel within the hole, simulated the exhaust nozzle. In order to disperse fuel throughout the void in the reflector, it was necessary to place aluminum cylinders of various sizes in the hole. The cylinders were 5.08, 10.16 and 20.32 cm outside diameter. The aluminum wall thickness in each case was 0.0965 cm.

The equivalent of 36 fuel sheets, approximately 94 grams of fuel, were placed on the inner surface of the aluminum wall forming the 30.5 cm void. The fuel was placed in a two row spiral along the full length of the nozzle. There was a $0.255 \pm 0.020\% \Delta k$ increase in k-excess. The next step was to load the aluminum cylinders without any fuel on them. There was a slight increase in reactivity of $0.005 \pm 0.027\% \Delta k$ due to the aluminum. The additional fuel was then added by placing two sheets of fuel per stage (12 stages) on the 10.16 and 20.32 cm diameter cylinders and one per stage on the 5.08 cm tube. One additional sheet was placed on the 20.32 cm cylinder making a total of 61 fuel sheets on the three cylinders. This addition of fuel (approximately 160 grams) increased k-excess $0.376 \pm 0.038\% \Delta k$. The total change was, therefore, equal to $0.636 \pm 0.051\% \Delta k$ including the aluminum and approximately 254 grams of Orallo. The cavity fuel loading was the same as during the power mapping of the injector tube wrapped with 0.0254 cm of cadmium around it or 5733.5 equivalent size 1.0 sheets (15.02 kg).

The results of a single power distribution measurement are given in Table 9.1 and Figures 9.1 and 9.2. It should be kept in mind that the fuel was dispersed as uniformly as possible but was still lumped to some extent in the form of solid sheets. In spite of this, the data appear to be reasonably smooth, as shown in Figure 9.1. The inner surface of fuel shows some minor data scatter but nothing very significant. There was an average flux attenuation from the outer surface to the center of the nozzle of 5.7% as determined from the averages given in this figure.

The radial power profile was essentially a straight line, as seen from Figure 9.2. The inner point was below the curve and also low in the axial curve. If the point is corrected to the axial curve, it matches the straight-line radial data very well. The weighted average of 2.208 was obtained by weighting the points on the various fuel positions by the amount of fuel on each cylinder and nozzle wall.

The average power-per-gram of fuel in the nozzle with respect to a watt of power-per-gram of fuel at the core center was as follows:

$$(1.667 \times 2.208) / 2.265 = 1.625$$

The ratio of the total relative power in the nozzle to the total relative power in the cavity was as shown below:

$$\frac{1.625 \times 254}{1.310 \times 1.119 \times 15.02 \times 10^3} = \frac{412.75}{22.02 \times 10^3} = 1.87 \times 10^{-2}$$

The axial power profile for the cavity (shown in Figure 9.3) was essentially as observed before except at the separation plane. This point increased considerably due to having the plug removed. This increase was discussed in Section 7.0. There was no significant change in the axial power profile caused by the addition of fuel to the exit nozzle except close to the nozzle where the specific power was enhanced about 8% (Reference Figure 7.3).

Power distribution measurements were made with all rods withdrawn except actuators 1 and 6 which were 46.0 and 0.0 cm withdrawn, respectively. The D₂O temperature was nominally 29°C.

TABLE 9.1
Catcher Foil Data - Configuration 10

Run 1029				
Foil No.	Location Radial (cm)	Axial (cm)	Normalized Counts (1)	Ratio of Local to Core Center (Foil No. X)
29	0	212.0	93804	1.512
30	0	196.8	71902	1.159
31	0	181.5	64330	1.037
32	0	166.3	65292	1.053
33	0	151.1	62023	1.000 (X)
34	0	135.8	71040	1.145
35	0	120.6	66154	1.067
36	0	105.2	73371	1.183
37	0	90.1	96995	1.564
Inside Exhaust Nozzle				
1		212.0	94984	1.531
2		217.08	104360	1.683
3		224.70	125804	2.028
4		232.32	128508	2.072
5		239.94	137328	2.214
6		247.56	126011	2.032
7		255.18	118464	1.910
8		262.80	108462	1.749
9		270.42	88392	1.434
10		278.04	76368	1.231
11		285.66	55304	.892
12		293.28	43561	.702
13		300.90	28912	.466
Outside Exhaust Nozzle				
14		212.0	92325	1.489
15		217.08	108236	1.745
16		224.70	134056	2.161
17		232.32	143977	2.321
18		239.94	147165	2.373
19		247.56	140512	2.265
20		255.18	126120	2.033
21		262.80	112244	1.810
22		270.42	94599	1.525
23		278.04	80309	1.295
24		285.66	63038	1.016
25		293.28	45908	.740
26		300.90	25453	.410
27	5.1	247.56	133585	2.154
28	10.2	247.56	137652	2.219

(1) Normalization to 100,000 counts on decay corrector.

Fig. 9.1 Axial power distribution from bare catcher foils in exhaust nozzle - configuration 10

Fig. 9.2 Radial power distribution from bare catcher foils in exhaust nozzle - configuration 10

Fig. 9.3 Axial power distribution from bare catcher foils at center of core - configuration 10

10.0 CONFIGURATION 4

This configuration consisted of a fuel radius of 61.0 cm (0.67 of cavity radius) and a 10.16 cm thick, segmented beryllium reflector in the D_2O tank. The beryllium was in rectangular sections nominally 40.64 cm wide by 109.22 cm long. A support plate was bolted to the ends of each beryllium block and on each support plate were four rollers. The rollers fit inside of rails in the radial reflector tank. This permitted easy insertion of the beryllium around the cavity region from the top of the tank. The support plates contained three sets of bolt holes which allowed three different radial positions for the beryllium slabs. Configuration 4 required the beryllium to be against the cavity wall. Some clearance was required to assure easy insertion of the beryllium, so at the closest point, the separation distance between the outer surface (wet surface) of the cavity wall and the tangent to the beryllium slabs was 0.8 cm. The average distance from the cavity wall over a 40.64 cm wide slab was an additional 0.75 cm for a total distance of 1.55 cm.

Two aluminum trays were constructed to fill in at the top of the reflector region as required to complete the beryllium reflector. Each tray used was filled with beryllium pieces of varying sizes to a thickness of 10.16 cm. Where the rectangular blocks joined together, a triangular region of D_2O was formed since the blocks physically touch at the inner radius but there was a gap at the outer radius of the beryllium. No attempt was made to fill this region with beryllium. Thus, within the 10.16 cm radial beryllium thickness, nominally 4% of the volume was D_2O .

In order to obtain foil data from the radial reflector, a water tight aluminum tube was placed through the hatch in the top of the reflector tank. This tube extended through the D_2O to the cavity wall. The beryllium blocks were positioned so that the tube would pass between the point where two slabs joined. It was necessary to force a small gap at the inner radius of about 0.635 cm to accommodate the tube. No small pieces of beryllium were placed around the tube over the 10.16 cm beryllium region to fill in the small triangular region of D_2O at the ends of the beryllium slabs.

10.1 Rod Worth and Reactivity Measurements

Configuration No. 4 was tested after Configuration 6 measurements were completed. Configuration 6 had the 10.16 cm beryllium reflector in the D_2O at 10.8 cm from the outer surface of the cavity wall. The reactor contained 7503.5 sheets of Orallo and k -excess was $0.983\% \Delta k$ before moving the beryllium in to 0.8 cm from the outer surface of the cavity wall. It was necessary to increase the fuel loading to 8173.5 sheets of fuel (21.5 kg) to compensate for the reactivity loss due to the beryllium movement. The resultant configuration had an excess reactivity of $0.313\% \Delta k$ with actuator 6 at 21.0 cm withdrawn and all other rods out. The measured increase in fuel loading was 1775 grams and the final loading arrangement was as shown in Table 10.1.

Fuel worth measurements at the core center and outer edge gave $(0.48 \pm 0.076) \times 10^{-3} \% \Delta k / \text{gm}$ and $(1.401 \pm 0.072) \times 10^{-3} \% \Delta k / \text{gm}$, respectively. The standard error was based on an estimated error per period measurement

of 0.005 % Δk . This gave a ratio of fuel worth from the edge of the fuel to the core center of 2.9. The power distribution from catcher foils in the core gave a power ratio from the outer edge of the fuel to the core center of 2.27. Since time did not permit detailed measurements of fuel worth vs. core radius, it was necessary to assume some relation between power distribution and fuel worth. As will be discussed in Section 11.0, it was found by a single measurement of fuel worth near the outer edge of the fuel in addition to the core edge and core center fuel worth measurements, that except at the very outer edge of the fuel, the fuel worth does follow the power distribution curve. The power distribution data were, therefore, used in conjunction with the worth at the outer edge and center of the fueled region. It was observed that the fuel worth at the core center gave a much lower fuel worth than the outer edge value. Comparing with the same values for Configurations 5 and 6, it was determined that the core center fuel worth data were in error. Only the outer edge fuel worth was used, therefore, to get an average core fuel worth of $(1.073 \pm 0.055) \times 10^{-3}$ % Δk /gm. The average fuel worth for Configuration 6 was $(1.074 \pm 0.113) \times 10^{-3}$ % Δk /gm which is the same as above. Using an average value for the two configurations of $(1.074 \pm 0.089) \times 10^{-3}$ % Δk /gm and the two k-excess values, the following value is obtained for moving the beryllium from 10.8 to 0.8 cm:

$$(0.313 \pm 0.006) - [(0.983 \pm 0.020) + 1775 \times (1.074 \pm 0.089) \times 10^{-3}] = -2.576 \pm 0.159 \text{ \%}\Delta k$$

Adding to this, the change in excess reactivity due to placing the beryllium at 10.8 cm of -5.298 ± 0.328 % Δk , the total loss of reactivity due to placing the beryllium 0.8 cm from the cavity wall was -7.873 ± 0.343 % Δk .

Prior to adding fuel after the beryllium had been positioned at 0.8 cm from the cavity wall, the reactor was subcritical. Subcritical counts were taken on two of the three count rate channels. These counts were continued as increments of fuel were placed in the reactor. The data obtained were as follows:

Rod Positions (Act. 1 to 6)	Channel 1 <u>CR₀/CR</u>	Channel 2 <u>CR₀/CR</u>	Reactor Condition
Rods In	0.0542	0.0543	Be at 0.8 cm, no
Rods Out	0.0110	0.0112	extra fuel. Base
Rods In	0.0489	0.0502	470.4 gm fuel
Rods Out	0.0074	0.0079	added to reactor
Rods In	0.0410	0.0423	867.1 gm fuel
Rods Out	0.0008	0.0009	added to reactor
Rods In	0.0372	0.0395	437.5 gm fuel
Rods Out	Reactor critical with 0.313 % Δk excess reactivity.		added to reactor

Based on "rods out" data for the first two increments of fuel addition, multiplication increased about $1.03 \pm 0.03\% \Delta k$. This is an estimated error. The final increment of fuel was worth about $0.314 \pm 0.006\% \Delta k$. The estimated worth of placing the beryllium at 0.8 cm from the cavity wall using these data would be as follows:

$$(0.313 \pm 0.006) - (0.983 \pm 0.020) - (1.03 \pm 0.05) - (0.314 \pm 0.006) - (5.298 \pm 0.328) = -7.312 \pm 0.332 \% \Delta k$$

Within the possible standard error, this value and the one given above ($-7.873 \pm 0.343 \% \Delta k$) are close to the same.

A single rod bump on actuator 6 gave a worth of $-0.797\% \Delta k$. This was 10% higher than the value measured for this actuator on Configuration 3B.

10.2 Power Distribution Measurements - Bare Catcher Foils

Only bare catcher foil data were obtained in the cavity for this configuration and the measurements were made with all rods withdrawn except actuator 6 which was nominally 24 cm withdrawn. The average D_2O temperature during the foil exposures was about $28^\circ C$. The results are given in Table 10.2 and Figures 10.1 and 10.2. The weighted average radial at the axial center of the core over the fueled region was 1.398. This compared to 1.310 for Configuration 3B. The peak power at the outer edge of the fuel for Configuration 4 was a factor of 2.27 above the core center whereas this factor was 1.83 for Configuration 3B. This steeper radial power gradient associated with Configuration 4 was due, at least in part, to the additional 6.5 kg of fuel (43.3% increase) required to compensate for the loss in reactivity when placing the beryllium near the cavity wall. This additional fuel also included the fuel additions prior to the moderator temperature coefficient measurement.

The axial power at the radial center of the core showed similar changes observed for the radial power profile compared to Configuration 3B. The axial power distribution average increased from 1.124 to 1.208. This is a 7.5% increase and compares well with the 6.7% increase in the radial weighted averages noted above. The ratio of the power at the control rod end of the cavity to the core center was 1.91 compared to 1.53 for Configuration 3B. At the opposite end of the core, this ratio was 2.17 whereas the same value for Configuration 3B was 1.64.

10.3 Resonance Detector Data - Gold Foils

10.3.1 Bare Gold Data

Bare gold foil data were obtained within the cavity and in both the radial and end reflector as with the other configurations. The information on the exposed foils is presented in Table 10.3. This table also includes the cadmium covered gold foil data. As with the gold foil data from the other configurations, it was power normalized to Run 1002 or to a catcher foil normalizer activity at 50 minutes after

shutdown of 79464 counts per minute. The normalized power level for the reactor was as follows:

$$\frac{79464 \times 43558}{100000} \times \frac{123.2}{3.2 \times 10^{10}} \times 1.398 \times 1.208 \times 21.5 \times 10^3 \times$$

$$0.932 = 4.51 \text{ watts}$$

The normalized power at the core center calculated to be 1.33×10^{-4} watt/gm-U-235. The power normalization data for this configuration are given in Table 10.4.

The relative radial flux profile within the cavity at the axial center is shown in Figure 10.3. The data were normalized to the gold foil activity at the core center. The weighted average radial over the fueled region was 1.166 and the ratio of the flux at the edge of the fuel to the core center was 1.52. Similar data were not obtained for configuration 3B but were available for Configuration 3A. Compared to Configuration 3A, there was a general increase in the flux gradients with this arrangement as the weighted radial average for Configuration 3A was 1.156 and the ratio of the flux at the outer edge of the fuel to the core center was 1.43. The 6% increase in the ratio of the flux from the edge to the center of the fueled region was undoubtedly due to the higher fuel loading for Configuration 4.

The axial flux distribution obtained from the gold foil data at the radial center of the cavity is given in Figure 10.4. The average was 1.124. Compared again to Configuration 3A, there was a 6% increase in the average curve. The relative flux at both ends of the core with respect to the core center also increased compared to Configuration 3A. The increase at the ends of the core was slightly over 10% which was consistent with but slightly higher than the observed radial change in flux distribution obtained from the radial foils.

The relative flux distribution in the radial and end reflectors is presented in Figure 10.5. Compared to the same power base as Configuration 3A there was no significant change in the relative flux profile in the radial reflector except for a possible slight broadening of the peak in the D_2O . In order to check the relative flux distribution in the radial reflector and obtain a more detailed curve, a gold wire was exposed in the tube where the foils were placed. The comparison of the foil and wire data is shown in Figure 10.6 on a relative basis. As will be observed, the two sets of data show very good agreement.

10.3.2 Cadmium Ratios

The cadmium ratios resulting from the bare and cadmium covered foil data are presented in Table 10.5. The cadmium ratio profiles in the end and radial reflectors are shown in Figure 10.7. At the inner-most points of both the radial and end reflectors, there was a 14 to 15% decrease in the cadmium ratios compared to Configuration 3A. This decrease was apparently due to the harder spectrum within the cavity which was primarily a result of the 43% heavier fuel loading rather than an effect of the beryllium in the radial reflector. The

fact that there was essentially the same effect at this point in the end reflector as in the radial reflector would also substantiate this conclusion. The end reflector actually experienced the greatest change and the harder flux was still observed at 15.2 cm into the end reflector as the cadmium ratio was 9.4% lower at this point for Configuration 4 than Configuration 3A.

Within the fueled region, there was a general decrease in the cadmium ratio of 14% compared to Configuration 3A. At the outer edge of the fuel and at the axial center of the core, the cadmium ratio decreased as much as 18%. These values agree well with the changes observed within the D_2O region near the cavity walls.

10.3.3 Thermal Neutron Flux Distribution - Gold Data

The calculated thermal flux based on the gold foil data for Configuration 4 are given in Table 10.6 and Figures 10.8 and 10.9. The flux values were calculated according to the procedure given in Section 4.4.3. Table 10.6 also shows a comparison with Configurations 3A and 3B. The approximate 20% increase due primarily to removal of the end plug in thermal flux along the axial center line of the cavity in going from Configuration 3A to 3B was eliminated and was in fact, about 25% below Configuration 3A. Part or most of this change would be due to the increase in fuel loading from 14.5 to 21.5 kg, a 48% increase. Sufficient data were not available near the radial core boundary for comparison but a corresponding change is indicated for that location from the single radial traverse obtained.

The radial reflector in the region of the peak flux showed an increase of about 10% over Configuration 3B but just slightly higher than Configuration 3A. The thermal flux beyond the peak shows a general increase over both Configurations 3A and 3B, an effect which is indicative of the higher than normal fast flux in the region of the beryllium when compared with no beryllium in the reflector. Some of the additional fast flux arises from the $(n, 2n)$ reaction in the beryllium, an effect responsible for a calculated 6% of the fast neutrons in this system.

The end reflector shows about a 4% increase in thermal flux over Configuration 3A and about a 17% increase over Configuration 3B. The harder spectrum within the cavity due to the heavier fuel loading undoubtedly contributes in part to the higher thermal flux in the end reflector as the greater abundance of higher energy neutrons result in a higher relative thermal flux in the D_2O where the neutrons are thermalized.

TABLE 10.1

Critical Fuel Tray Loading Arrangement - Configuration 4

Tray No.	Number of Surfaces	Fuel Sheets per Tray (1)	Fuel Weight (2) (gm)
1	2	36	94.3
2	8	128	335.4
3	10	155	406.1
4	12	207	542.3
5	14	243	636.7
6	14	224	586.9
7	16	264	691.7
8	16	251	657.6
9	18	279	731.0
10	18	306	801.7
11	18	279	731.0
12	20	323	846.3
13	20	330	864.6
14	20	320	838.4
15	20	310	812.2
16	20	343	898.7
17	20	310	812.2
18	20	320	838.4
19	20	330	864.6
20	20	323	846.3
21	20	310	812.2
22	20	340	890.8
23	18	279	731.0
24	18	291	762.4
25	18	305	799.1
26	16	257.5	674.6
27	16	248	649.8
28	14	238	623.6
29	12	186	487.3
30	12	195	510.9
31	8	133	348.5
32	6	110	288.2
Totals	504	8173.5	21414.8 (3)

(1) Equivalent size 1.0 fuel sheets

(2) Weights based on 2.62 grams per sheet

(3) Measured weights of fuel added since Configuration 3B gives 21.5 kg

TABLE 10.2
Catcher Foil Data - Configuration 4

Run 1042

Foil No.	Type	Location		Tray No.	Normalized Counts (1)	Ratio of Local to Core Center (Foil No. X)
		Radial (cm)	Axial (cm)			
1	Bare	0	212.0	16	94802	2.176
2	Bare	0	196.8	16	56785	1.304
3	Bare	0	181.5	16	45829	1.052
4	Bare	0	166.3	16	43832	1.006
5	Bare	0	151.1	16	43558	1.000 (X)
6	Bare	0	135.7	16	47941	1.100
7	Bare	0	120.6	16	47078	1.081
8	Bare	0	105.3	16	58408	1.341
9	Bare	0	90.1	16	83294	1.912
10	Bare	15.2	151.1	16	44137	1.013
11	Bare	30.5	151.1	16	48632	1.116
12	Bare	45.7	151.1	16	56069	1.287
13	Bare	61.0	151.1	16	99001	2.273
14	Bare	76.2	151.1	16	116455	2.674
15	Bare	91.4	151.1	16	115571	2.653

(1) Normalization to 100,000 counts on decay corrector.

TABLE 10.3

Gold Foil Data - Configuration 4

No.	Foil Type	Location		Activity (CPM) (1)	Foil Wt. (gm)	Specific Activity d/m/gm $\times 10^{-5}$ (2)
		Radial (cm)	Axial (cm)			
10	Bare	15.2	151.1	4169	.0335	5.801
11	Bare	30.5	151.1	4840	.0376	6.001
12	Bare	45.7	151.1	5429	.0384	6.591
13	Bare	61.0	151.1	7637	.0408	8.726
14	Bare	76.2	151.1	8620	.0415	9.683
15	Bare	91.4	151.1	7783	.0369	9.832
16	Bare	0	89.4	6649	.0338	9.170
17	Bare	0	74.9	13623	.0318	19.970
18	Bare	0	59.6	15176	.0409	17.297
19	Bare	0	44.4	9221	.0348	12.352
20	Bare	0	29.1	5577	.0349	7.449
21	Bare	0	13.9	3391	.0418	3.782
22	Bare	0	0	458	.0410	0.521
23	Bare	93.2	151.1	7128	.0282	11.783
24	Bare	107.7	151.1	11531	.0339	15.856
25	Bare	123.0	151.1	10405	.0385	12.599
26	Bare	138.2	151.1	7289	.0402	8.452
27	Bare	153.5	151.1	4657	.0414	5.244
28	Bare	168.7	151.1	2366	.0431	2.559
29	Bare	183.4	151.1	278	.0390	0.332
30	Bare	91.4	212.0	7832	.0386	9.459
31	Bare	91.4	90.1	8637	.0392	10.271
32	Cd	91.4	90.1	2351	.0357	3.070
33	Cd	91.4	212.0	1606	.0182	4.114

Run 1043

3	Cd	0	120.6	2926	.0379	3.625
2	Cd	0	181.5	2999	.0406	3.468
1	Cd	0	212.0	2722	.0325	3.933
8	Bare	0	82.5	13011	.0360	16.970
9	Bare	0	67.2	13691	.0333	19.305
10	Bare	0	52.0	11323	.0356	14.934
11	Bare	0	36.8	8983	.0425	9.924
4	Cd	45.7	151.1	2795	.0361	3.635
5	Cd	93.2	151.1	3310	.0376	4.133
6	Cd	123.0	151.1	279	.0367	0.357
7	Cd	153.5	151.1	1	.0325	0.001

TABLE 10.3
(Continued)

No.	Foil Type	Location		Activity (CPM) (1)	Foil Wt. (gm)	Specific Activity
		Radial (cm)	Axial (cm)			d/m/gm $\times 10^{-5}$ (2)
Run 1044						
9	Bare	0	90.1	7114	.0416	8.290
8	Bare	0	105.3	1356	.0348	1.890
7	Bare	0	120.6	3733	.0273	6.628
6	Bare	0	135.8	4720	.0385	5.943
5	Bare	0	151.1	4718	.0399	5.732
4	Bare	0	166.3	3730	.0302	5.987
3	Bare	0	181.5	4698	.0385	5.915
2	Bare	0	196.8	4536	.0333	6.603
1	Bare	0	212.0	6494	.0373	8.439
Run 1045						
1	Cd	0	151.1	2413	.0302	3.833
2	Cd	0	105.3	2771	.0328	4.052
3	Cd	30.5	151.1	2824	.0360	3.763
4	Cd	61.0	151.1	3609	.0475	3.645
5	Cd	91.4	151.1	3313	.0388	4.096
6	Cd	0	89.4	2900	.0307	4.531
7	Cd	0	59.6	602	.0389	0.742
8	Cd	0	29.1	12	.0421	0.014
9	Bare	100.1	151.1	11531	.0337	15.570
10	Bare	115.4	151.1	11924	.0379	15.091
11	Bare	130.6	151.1	9149	.0411	10.678
12	Bare	145.8	151.1	5733	.0400	6.875
Run 1046						
1	Cd	0	196.8	2746	.0364	3.517
2	Cd	0	90.1	3293	.0384	3.998
3	Cd	0	74.9	2329	.0343	3.165
4	Cd	0	44.4	77	.0293	0.123
5	Cd	107.7	151.1	1415	.0391	1.687
6	Cd	138.2	151.1	34	.0371	0.043

(1) Observed activity corrected to shutdown time.

(2) Specific activity is the disintegration per minute per gram at shutdown normalized for power to Run 1002.

TABLE 10.4
Power Normalization Factors - Configuration 4

Run	Time	Decay Time (min)	Decay Factor	Activity (GPM)	Corrected Activity (CPM) (1)	Norm Factor
1042	2058.03	41.78	.810	356403	288686	.276
	2059.40	43.15	.841	342737	288242	
	2100.76	44.51	.870	331175	288122	
					<u>288350</u>	
1043	2308.89	38.76	.749	384179	287751	.278
	2310.90	40.77	.780	364257	284120	
	2312.69	42.56	.825	347495	286683	
					<u>286185</u>	
1044	2406.09	16.57	.340	829620	282071	.287
	2407.38	17.86	.351	782161	274539	
	2408.70	19.18	.380	720257	273698	
					<u>276769</u>	
1045	0957.31	28.25	.525	532207	279409	.284
	0958.58	29.52	.550	509939	280466	
	0959.92	30.86	.572	488213	279258	
					<u>279711</u>	
1046	1222.54	56.18	1.140	251426	286626	.276
	1223.80	57.44	1.172	244786	286889	
	1225.26	58.90	1.220	238016	290380	
					<u>287965</u>	

(1) Activity decay corrected to 50 min. after shutdown.

TABLE 10.5
Gold Foil Cadmium Ratios - Configuration 4

Location		d/m/gm $\times 10^{-5}$	d/m/gm $\times 10^{-5}$	Cd Ratio	Corrected Cd Ratio
Radial (cm)	Axial (cm)				
0	0	0.521	0.00025 (1)	2084.00	897.00
0	13.9	3.782	0.0016 (1)	2364.00	1017.00
0	29.1	7.449	0.0137	544.00	2.17
0	44.4	12.352	0.1225	101.00	47.13
0	59.6	17.297	0.742	23.31	10.20
0	74.9	19.970	3.165	6.31	3.29
0	89.4	9.170	4.531	2.02	1.48
0	90.1	8.290	3.998	2.07	1.46
0	121.5	--	4.052	--	--
0	151.1	6.628	3.625	1.83	1.29
0	181.5	5.732	3.833	1.50	1.27
0	196.8	5.915	3.468	1.71	1.28
0	212.0	8.439	3.933	2.15	1.53
0	151.1	5.732	3.833	1.50	1.27
30.5	151.1	6.597	3.763	1.75	1.31
61.0	151.1	8.726	3.645	2.39	1.50
91.4	151.1	9.832	4.096	2.40	1.57
93.2	151.1	11.783	4.133	2.85	1.72
107.7	151.1	15.856	1.687	9.40	4.43
123.0	151.1	12.599	0.357	35.29	15.47
138.2	151.1	8.452	0.0427	198.00	83.71
153.5	151.1	5.244	0.00722 (1)	726.00	322.00
168.7	151.1	2.559	0.0011 (1)	2326.00	1001.00
183.9	151.1	0.332	0.00017 (1)	1953.00	840.00
91.4	90.1	10.271	3.070	3.35	2.02
91.4	212.0	9.459	4.114	2.30	1.85

(1) Extrapolated value from other cadmium covered foil data.

TABLE 10.6

Thermal Neutron Flux - Configuration 4

Location		A(1)	Thermal Flux	
Radial (cm)	Axial (cm)		B(2)	C(3)
0	0	0.18	1.059	1.111
0	13.9	1.30	1.040	1.140
0	29.1	2.56	0.992	1.180
0	44.4	4.21	1.047	1.203
0	59.6	5.71	1.059	--
0	74.9	5.75	1.027	1.234
0	89.4	1.66	0.802	0.922
0	90.1	1.52	0.652	0.710
0	121.5	0.86	0.723	--
0	151.1	0.80	0.721	0.680
0	181.5	0.82	0.732	0.631
0	196.8	1.02	--	--
0	212.0	1.63	0.953	0.799
0	151.1	0.80	0.721	0.580
30.5	151.1	0.95	0.779	--
61.0	151.1	1.67	0.780	--
91.4	151.1	1.95	0.789	--
93.2	151.1	2.46	0.842	0.943
107.7	151.1	4.84	0.988	1.112
123.0	151.1	4.22	1.012	--
138.2	151.1	2.90	1.028	1.124
153.5	151.1	1.80	1.040	1.146
168.7	151.1	0.88	0.967	1.023
183.9	151.1	0.12	0.444	0.506

- (1) Column A gives the thermal flux in $\text{n/cm}^2/\text{sec/watt} \times 10^{-6}$ for Configuration 4.
- (2) Column B is the ratio of thermal flux in Configuration 4 to Configuration 3A.
- (3) Column C is the ratio of thermal flux in Configuration 4 to Configuration 3B.

Fig. 10.1 Radial power distribution from bare catcher foils at an axial position of 151.1 cm - configuration 4

Fig. 10.2 Axial power distribution from bare catcher foils at core center - configuration 4

Fig. 10.3 Radial distribution of bare gold foil activity at the cavity at an axial position of 151.1 cm - configuration 4

Fig. 10.4 Axial distribution of bare gold foil activity in the cavity at core center - configuration 4

Fig. 10.5 Bare gold foil activity distribution in the reflector - configuration 4

Fig. 10.6 Bare gold foil and wire activity distribution in the radial reflector - configuration 4

Fig. 10.7 Gold cadmium ratios in the radial and end reflectors - configuration 4

Fig. 10.8 Thermal neutron flux distribution radially through axial center of core - configuration 4

Fig. 10.9 Thermal neutron flux distribution axially through radial center of core - configuration 4

11.0 CONFIGURATION 5

This configuration was the same as Configuration 4 except for the beryllium position which was moved from 0.8 cm to 5.8 cm from the inner surface of the D₂O. Initially the fuel loading was the same as Configuration 4 and the reactor arrangement is designated as Configuration 5A. Later in the experiment, additional measurements were requested with the uniformly loaded core and the beryllium at 5.8 cm. The reactor was restored to the desired condition but with less total fuel in the reactor and is identified as Configuration 5B. The experiments associated with these two configurations will be discussed separately.

11.1 Configuration 5A

The arrangement of fuel within the reactor at the time the beryllium was moved from 0.8 to 5.8 cm from the inner surface of the D₂O is given in Table 10.1. This loading was unchanged for Configuration 5A. At the conclusion of testing on this configuration, the fuel was removed from the reactor and carefully counted and weighed. The total count gave 3042 size 1.5 and 3613 size 1.0 sheets or 8176 equivalent size 1.0 sheets. Table 10.1 shows 8173.5 equivalent size 1.0 sheets for a difference of 2.5 sheets. Considering the number of sheets involved, the agreement is excellent.

The total fuel weighed 21.53 kg. On the average, the size 1.5 sheets weighed 3.95 ± 0.01 grams per sheet and the size 1.0 sheets weighed 2.63 ± 0.01 grams per sheet. The total weight agrees very well with the weight given in Table 10.1 of 21.5 kg as a note at the bottom of the page. The average weight of 2.62 ± 0.06 grams per sheet obtained when unloading Configuration 1 is 0.4% lower than the above weight per sheet and within the given uncertainties.

11.1.1 Rod Worth and Reactivity Measurements

The 5 cm movement of the 10.16 cm thick beryllium reflector in the D₂O tank resulted in a k -excess of 3.098 ± 0.097 , a $2.785 \pm 0.077\% \Delta k$ increase in k -excess. Placing the beryllium at 0.8 cm from the cavity caused a decrease of $7.873 \pm 0.343 \% \Delta k$ as given in Section 10.1. The difference between these two quantities ($-5.088 \pm 0.351 \% \Delta k$) is the expected total reactivity penalty of placing the 4-inch thick beryllium reflector at 5.8 cm from the cavity wall.

Fuel worth measurements were obtained at three radial locations in this core configuration. The values obtained are as follows:

<u>Location</u>	<u>Fuel Worth ($\% \Delta k$/gm)</u>
Core Center	$(0.604 \pm 0.091) \times 10^{-3}$
49 cm from Core Center	$(0.885 \pm 0.084) \times 10^{-3}$
Outer Edge of Fuel	$(1.643 \pm 0.050) \times 10^{-3}$

The ratio of the value at 49 cm to the core center was 1.465. The same ratio from the power distribution data (bare catcher foils) was 1.45. The two values agree very closely indicating the fuel worth to follow the same general curve shape as the power from the center of the core to a region close to the outer edge of the fuel. The average fuel worth for the core as calculated from the power distribution and fuel worth data was $1.010 \pm 0.106 \text{ } \%\Delta k/\text{gm}$. For Configuration 3B the value was $1.516 \text{ } \%\Delta k/\text{gm}$, uncertain error. The average of these two numbers is $1.263 \pm 0.106 \text{ } \%\Delta k/\text{gm}$ which can be used in conjunction with the differences in k-excess to determine the worth of placing the Be at 5.8 cm as follows:

$$(3.098 \pm 0.093) - [(2.783 \pm 0.083) + 4476 \times (1.263 \pm 0.106 \times 10^{-3})] = -5.338 \pm 0.490 \text{ } \%\Delta k$$

Within the experimental error, this value is the same as the above number.

Three rod worth measurements were obtained during the reactivity measurements and the results are as follows:

<u>Actuator</u>	<u>Reactivity Worth ($\%\Delta k$)</u>
1 to 6 (17 rods)	-4.412
3 (3 rods)	-0.860
7 (3 rods)	-0.658

These were single measurements so no error is given.

11.1.2 Power Distribution Measurements - Bare Catcher Foils

Only bare catcher foil data were obtained within the fueled region. The results are given in Table 11.1 and Figures 11.1 and 11.2. The only change between configurations 4 and 5A was the shift in beryllium position. The fuel loading was unchanged. The increase in excess reactivity was held in the control system thus requiring insertion of rods in the end reflector. The first power distribution run (Run 1047) was with Trays 1 and 32 out of the reactor. Actuators 4, 5 and 6 were fully inserted and Actuator 3 was about 14.8 cm withdrawn. The remaining foil data were obtained with all trays in the reactor and Actuators 3, 4, 5 and 6 fully inserted and one other actuator partially inserted. The D_2O temperature was nominally $28^\circ C$ during all foil exposures.

The weighted average radial power over the fueled region was 1.359 for this configuration compared to 1.398 for configuration 4 or a decrease of 2.8% for Configuration 5A. The relative radial power at the edge of the fuel decreased from 2.27 for Configuration 4 to 2.13 for this configuration which was a 6.2% change.

The axial power distribution at the radial center of the core, shown in Figure 11.2, gave an average of 1.185 compared to 1.208

for Configuration 4. This is only a 1.9% difference. The points at the ends of the cavity both decreased about 9.5%. All of the catcher foil data show the same general decrease in power gradients due to moving the beryllium back 5 cm which would suggest a slight hardening of the spectrum. The control rods being inserted into the end reflector may have had some effect on these results. However, the axial power profile did not show any more relative power decrease at the control rod end of the core than at the separation plane. This would indicate the rod effect to be negligible or the effect was uniformly distributed over the entire fueled region.

11.1.3 Resonance Detector Data - Gold Foils

As with Configuration 4, gold foils were exposed in both the cavity and the end and radial reflectors. This included bare and cadmium covered foils. The data obtained are given in Table 11.2 and include both bare and cadmium covered foils. The foil disintegration rates were power normalized to Run 1002 using the values from Table 11.3.

It will be noted from Table 11.2 that the foil weights ranged from nearly 0.015 to 0.050 gm per foil. By the time this experiment was conducted, all of the 0.00127 cm thick foils had been used and it was necessary to go to 0.000508 cm thick foils. The thinner foils had less resonance self-shielding than the thicker foils thus producing a higher specific activity per gram of foil weight in the regions where the epi-cadmium foil activity was a significant portion of the total. Resonance self-shielding corrections were made on the bare foils by using both the bare and cadmium covered foil data, where available. The fraction of the bare foil activity due to epi-cadmium and sub-cadmium neutrons was determined and then the appropriate correction was applied to the fraction of the activity caused by the epi-cadmium neutrons. The equations used in the calculations are given in Section 4.4.3.

The results of these corrections are given in Table 11.2. The radial flux profiles in the core based on the corrected and uncorrected data are shown in Figure 11.3. It will be noted that this figure also contains a third curve which consists of the uncorrected data normalized to 1.01 at 15.2 cm from the center of the core. The reason for doing this was that the foil at the core center was 0.00127 cm thick while the others were all 0.000508 cm thick. Comparing the foils of the same thickness gave a radial distribution curve which was in line with the expected distribution and was on the same uncorrected basis as for previous gold data. The weighted average for this curve of 1.162 agrees very well with 1.166 for Configuration 4. The catcher foil data comparison between these two configurations did not show any significant change, therefore, the gold data would not be expected to change either. The axial flux profile from the gold foils is shown in Figure 11.4. The two curves include the corrected and uncorrected data as with the radial profile. The only foil in the group of axial foils which was not 0.00127 cm thick was the one at the control rod end of the core. On the uncorrected curve, this point was too high as would be expected. The point at the other end of the core was 8.2% lower than the same point from Configuration 4.

The average uncorrected curve was 1.111 compared to 1.124 for Configuration 4. The average for the corrected curve was 1.146. As will be noted here, there was no gross change in the averages. The average, however, has not been sensitive to significant changes in the core. The end points are normally the only areas of change and these affect the average very little.

Although these data are not as conclusive as would be desirable, it appears that no significant change in relative flux distribution occurred in the cavity when moving the beryllium from 0.8 cm to 5.8 cm from the cavity wall.

The relative flux distributions in the radial and end reflectors from the bare gold data are presented in Figure 11.5. The end reflector, compared to Configuration 4, showed a generally lower foil activity distribution which was due to rods being inserted into the reflector. The exact rod pattern used during these foil exposures is given in Section 11.1.2. The first foil exposures did not include any rods in the inner ring of actuators near the position where foils were exposed. In subsequent exposures, however, an adjacent actuator containing three rods was fully inserted. This additional rod shadowing caused a significant decrease in the activation flux as noted in Figure 11.5.

The radial reflector did not show any change due to changing the rod positions in the end reflector, as shown in the figure. Compared to Configuration 4, the flux peak in the radial reflector was narrowed and there was a decrease in flux level behind the beryllium.

The radial flux distribution was checked by exposing a gold wire in this region. The comparison between the wire and foils is shown in Figure 11.6. The foil data are generally higher than the wire results out to about 10 cm. From there on, there is good agreement. There appears to be a shift in the wire counter efficiency between 15 and 20 cm, which may account for the difference over the part of the curve near the cavity.

The cadmium ratio data obtained from gold foils in the cavity and reflector regions are given in Table 11.4. The distribution in the radial and end reflectors is presented in Figure 11.7. Out to about 35 cm in the radial reflector there was no measureable difference between configurations 4 and 5. There was however, an indicated drop in the cadmium ratio beyond about 35 cm. Out to 15 cm in the end reflector, the cadmium ratio was also unchanged over Configuration 4. Beyond this point, however, the control rods caused a definite hardening of the flux as would be expected.

Within the cavity, the gold foils did not show any measureable change in cadmium ratio except in the extreme corners where the radial and end tanks join. At the control rod end of the core, the cadmium ratio in the corner increased 4% compared to Configuration 4. At the separation plane, the cadmium ratio in the corner showed a 24% decrease. However, the bare foil activity looks suspiciously low for Configuration 5A in the corner at the separation plane.

11.1.4 Thermal Neutron Flux Distribution - Gold Data

The thermal flux calculated from the gold data for this configuration is shown in Table 11.4 and Figures 11.9 and 11.10. These data show more scatter than normal, resulting in some uncertainty as to the total change caused by the 5 cm movement of the beryllium. Within the active core, excluding the point at the control rod end of the cavity and at the radial center, there was an average $5 \pm 9\%$ increase in thermal flux in the cavity. The radial reflector showed a general decrease of $8 \pm 4\%$ not including the point at 183.9 cm. In the end reflector, the position of the control rods was very apparent as the thermal flux was depressed beyond the interface of the reflector and cavity.

11.2 Configuration 5B

The reactor was changed from a two zone loading (Configuration 8) back to the uniform loading containing 14 size 1.0 sheets per surface in two steps. The 10.16 cm thick beryllium was still at 5.8 cm from the inner surface of the D_2O . The total estimated fuel loading was 18.5 kg as shown in Table 11.5. With this fuel loading, k-excess was $0.621 \pm 0.010\% \Delta k$. This critical position was with all rods withdrawn except Actuator 7 which was 4.1 cm withdrawn.

11.2.1 Reactivity and Rod Worth Measurements

The difference in k-excess between Configurations 5A and 5B amounted to $2.477 \pm 0.094\% \Delta k$ for the removal of 3.0 kg of fuel. The worth per gram of fuel from these values would be $(0.826 \pm 0.031) \times 10^{-3} \% \Delta k / \text{gm}$ which is about 22% below the value given earlier in this section as a weighted average fuel worth. This lower value was unexpected and there is no obvious reason for the difference.

Configuration 5A k-excess was established at a D_2O temperature of 28°C . The D_2O temperature when Configuration 5B was initially established was 21°C and k-excess was $0.532 \pm 0.010\% \Delta k$. The D_2O was heated to 28°C to duplicate the same temperature as for Configuration 5A and k-excess increased to $0.621 \pm 0.010\% \Delta k$ for an increase of $0.089 \pm 0.014\% \Delta k$. This indicates a positive temperature coefficient which is the reverse of that expected with no Be in the reflector. However, the temperature range covered by the above results was below that covered by the temperature coefficient measurements reported in Section 7.4 so a direct comparison over the same temperature range was not possible.

Several reactivity measurements were made with this reduced fuel loading. The fuel in the reactor was shifted off-center by removing Tray 22 and moving Trays 23 to 32 up one position. Trays 1 to 11 were moved up one position and Tray 22 was inserted in position 11. This shifted the fuel off-center by 3.81 cm. Excess reactivity decrease $0.0458 \pm 0.0142\% \Delta k$. The fuel was shifted another 3.81 cm by removing Tray 21 and moving the trays in positions 22 to 31 up one position. The top 11 trays were moved up one position and Tray 21 was inserted in position 10. This reduced k-excess an additional $0.0526 \pm 0.010\% \Delta k$.

BeO was placed over a 55 degree sector of the Be reflector ring to determine the reactivity difference between the two materials. Equal volumes, 99880 cm^3 , of the two materials were used. There were 302.1 kg of BeO and 184.8 kg of Be used in the interchange. In each case, the material thickness was 10.16 cm distributed over the normal length of the Be, 109.2 cm. BeO was less reactive than Be by $0.314 \pm 0.050\% \Delta k$. A linear extrapolation of the reactivity loss due to replacing the Be with BeO at 5.8 cm from the cavity wall would be $2.06 \pm 0.33\% \Delta k$. Since calculations indicated BeO to be worth more than Be, the two materials were measured in a hydrogen-moderated critical experiment with a composition comparable to the MTR, but having the equivalent of 90% H_2O . The ratio of BeO worth to Be, each with respect to void was (0.896 ± 0.023) , again showing Be to be worth more.

Since the coolant for the cavity reactor will be hydrogen, it was of interest to know what reactivity effect it would have flowing between the fuel and D_2O . Polyethylene (CH_2) was originally chosen as the material to be used for the measurement. Carbon was also to be measured and its worth subtracted from polyethylene leaving only the hydrogen worth. It was requested by the NASA representative that at least a sector be mocked up with a hydrogen density of 2×10^{21} atoms/cc. The total void volume between the active core and the cavity wall was $1.77 \times 10^6 \text{ cm}^3$. To fill this region with the required hydrogen would require 41 kg of polyethylene. The first measurement was with a 0.0762 cm thick sheet approximately 121.9 cm square or 1058 gm. This was placed on top of the active core and caused k-excess to decrease about $0.6\% \Delta k$ which was much more than expected. The sheet was cut approximately in half leaving 548 gm in the reactor and was worth $-0.392 \pm 0.013\% \Delta k$, substantiating the first measurement. It was suspected that the material contained impurities so the worth of water was measured. An aluminum tray was first placed in the reactor to hold the water. This tray was placed at the bottom of the cavity in the void region. With 6.12 kg of Al in the core, k-excess decreased $0.200 \pm 0.012\% \Delta k$. The tray was 31.75 cm wide by 111.76 cm long. Distilled water weighing 2014.5 gm was then placed in the tray. This was worth $-0.238 \pm 0.009\% \Delta k$. On a per gram basis, water was worth a factor of 6 less than polyethylene.

In order to place 2×10^{21} atoms/cc hydrogen in the void region, it would take 53 kg of H_2O . A linear extrapolation of the worth of 2014.5 gm of H_2O to 53 kg gives a total worth of $-6.26 \pm 0.24\% \Delta k$. The worth of carbon was measured in the void region in the form of 10.16 cm square blocks of varied lengths. Two of these blocks weighing a total of 18.96 kg were measured to be worth $-0.0797 \pm 0.0100\% \Delta k$ or $(0.420 \pm 0.053) \times 10^{-5}\% \Delta k/\text{gm}$. If it is assumed that atom for atom carbon and oxygen have the same reactivity effect, which is a fairly good assumption, the oxygen in the water would be worth about $-0.19 \pm 0.02\%$. The net worth of 2×10^{21} atoms/cc in the void between the fuel and D_2O is $-6.07 \pm 0.24\% \Delta k$.

Ordinary tap water was also checked. With 2099.7 gm in the same aluminum tray used for the distilled water, k-excess decreased $0.2550 \pm 0.0103\% \Delta k$ which agrees very well with distilled water.

Because of the large reactivity penalty originally measured for polyethylene, the measurement was repeated later in the experiment. Strips of polyethylene about 30.5 cm wide were placed over the full length of the reactor so that the desired concentration of hydrogen atoms were in this sector. The strips of polyethylene were equally spaced about 5.08 cm from each other, across the void region, by using some aluminum screen material as spacers. A total of 2541 gm of polyethylene was worth $-0.720 \pm 0.022\% \Delta k$. Extrapolating to a total of 41 kg of polyethylene which would be required to equal the desired hydrogen density in the void region, gives a reactivity penalty of $-11.62 \pm 0.35\% \Delta k$. The carbon component was worth about $0.13\% \Delta k$.

The same polyethylene was used in each of the two measurements. Location of the material across the void region is, therefore, an important factor. It is apparently worth more next to the fuel than near the cavity wall. Since the H_2O measurements were near the cavity wall, the values are probably lower than would have been observed had it been possible to spread the water over the void region. The later polyethylene worth measurements should be the more accurate value.

Several rod worth measurements were made while obtaining the reactivity data. The following summarizes these results:

<u>Actuators</u>	<u>Reactivity Worth</u> \$ Δk
6	-0.724 ± 0.038
7	-0.715 ± 0.012
1 to 6	-4.648 ± 0.108
1 to 7	-5.116 (single measurement)

11.2.2 Resonance Detector Data

After reducing the fuel loading to about 18.5 kg, the cadmium ratios in the void region were measured using indium, gold, manganese and catcher foils. Foils were placed near the fueled region and near the D_2O to obtain cadmium ratios in each of these areas. It was necessary to perform the measurements in a single run so the foils were placed at least one foot from the ends of the core and it was assumed that there was little variation in cadmium ratio over the center two feet of the cavity region. The results from this measurement are given in Table 11.6. The gold, indium and manganese cadmium ratios have all been corrected for infinitely dilute foil activities. The gold foil cadmium ratios are from 3 to 4% higher than obtained for the heavier loaded core, which would be expected.

Following the above measurements in the void region, two aluminum trays with a total width of 77.5 cm filled with water to a depth of about 1.2 cm were placed in the void region at the bottom of the reactor and the cadmium ratio measurements repeated. A total of 19 kg of tap water was placed in the trays. The water volume was that required to

give 2×10^{21} atoms/cc of hydrogen over the region covered by the trays. The results are given in Table 11.7. A comparison between the two sets of data is as follows:

<u>Location</u>	<u>Ratio of Run 1064/Run 1063 (Cd Ratios)</u>			
	C.F.	Au	In	Mn
Next to fuel	0.92	1.01	1.12	1.41
Next to D ₂ O	1.10	1.21	1.12	1.13

There was a definite increase in cadmium ratio next to the D₂O caused by the water. Absolute flux calculations from the gold and indium data showed a 30 to 40% increase. The data next to the fuel were somewhat inconclusive but there is definitely indication of higher relative thermal flux or softer spectrum than prior to placing the water in the reactor. More data would have been desirable to define in more detail the possible effects of hydrogen, however, time did not permit more than a single measurement.

TABLE 11.1
Catcher Foil Data - Configuration 5A

<u>Run 1047</u>					
<u>Foil No.</u>	<u>Location</u>		<u>Tray No.</u>	<u>Normalized Counts (1)</u>	<u>Ratio of Local to Core Center (Foil No. X)</u>
	<u>Radial (cm)</u>	<u>Axial (cm)</u>			
1	0	212.0	16	92503	1.965
2	0	196.8	16	61067	1.297
3	0	181.5	16	49779	1.057
4	0	166.3	16	46309	0.984
5	0	151.1	16	47101	1.000
6	0	135.8	16	51144	1.086
7	0	120.6	16	51571	1.095
8	0	105.3	16	60770	1.291
9	0	90.1	16	81580	1.733
10	15.2	151.1	16	48050	1.021
11	30.5	151.1	16	51800	1.100
12	45.7	151.1	16	63429	1.347
13	61.0	151.1	16	109836	2.333
14	76.2	151.1	16	127598	2.710
15	91.4	151.1	16	128455	2.728

(1) Normalized to 100,000 counts on decay corrector.

TABLE 11.2
Gold Foil Data - Configuration 5A

Foil No.	Type	Location		Activity (CPM) (1)	Foil Wt. (gm)	Specific Activity	Corrected
		Radial (cm)	Axial (cm)			d/m/gm $\times 10^{-5}$ (2)	Activity d/m/gm $\times 10^{-5}$ (3)
Run 1047							
9	Bare	0	90.1	2950	.0142	9.228	11.206
8	Bare	0	105.3	5250	.0338	6.900	9.843
7	Bare	0	120.6	5447	.0399	6.064	8.181
6	Bare	0	135.8	5126	.0368	6.188	8.227
5	Bare	0	151.1	5440	.0414	5.837	7.579
4	Bare	0	166.3	5311	.0397	5.943	8.009
3	Bare	0	181.5	5023	.0358	6.233	8.247
2	Bare	0	196.8	5362	.0354	6.728	8.277
1	Bare	0	212.0	8558	.0483	7.871	12.316
10	Bare	15.2	151.0	2566	.0164	6.950	8.202
11	Bare	30.5	151.1	2656	.0160	7.374	8.840
12	Bare	45.7	151.1	3092	.0186	7.384	9.280
13	Bare	61.0	151.1	3851	.0164	10.431	13.171
14	Bare	76.2	151.1	4819	.0184	11.634	15.073
15	Bare	91.4	151.1	5257	.0204	11.447	15.213
16	Bare	0	89.4	4348	.0193	10.007	15.550
17	Bare	0	74.9	7201	.0171	18.706	23.204
18	Bare	0	59.6	5758	.0177	14.451	16.063
19	Bare	0	44.4	3050	.0152	8.913	9.165
20	Bare	0	29.1	1806	.0153	5.243	5.243
21	Bare	0	13.9	892	.0163	2.431	2.431
22	Bare	0	0	147	.0177	0.369	0.369
23	Bare	93.2	151.1	6095	.0211	12.831	18.216
24	Bare	107.7	151.1	5716	.0167	15.204	17.635
25	Bare	123.0	151.1	4743	.0182	11.576	12.236
26	Bare	138.2	151.1	3363	.0192	7.781	7.913
27	Bare	153.5	151.1	1712	.0153	4.970	4.970
28	Bare	168.7	151.1	1205	.0209	2.561	2.561
29	Bare	183.9	151.1	168	.0183	0.408	0.408
30	Bare	91.4	212.0	3503	.0193	8.062	11.239
31	Bare	91.4	90.1	4450	.0171	11.560	16.320
32	Cd	91.4	90.1	1641	.0155	4.703	
33	Cd	91.4	212.0	1741	.0158	4.895	
Run 1048							
3	Cd	0	120.6	3039	.03905	3.575	
2	Cd	0	181.5	2951	.03805	3.563	
1	Cd	0	212.0	3106	.04170	3.422	
4	Cd	45.7	151.1	3032	.03745	3.719	
5	Cd	93.2	151.1	3431	.03540	3.684	
6	Cd	123.0	151.1	244	.03217	0.348	

TABLE 11.2
(Continued)

Foil No.	Type	Location		Activity (CPM) (1)	Foil Wt. (gm)	Specific Activity d/m/gm $\times 10^{-5}$ (2)	Corrected Activity d/m/gm $\times 10^{-5}$ (3)
		Radial (cm)	Axial (cm)				
7	Cd	153.5	151.1	9	.03352	0.012	
8	Bare	0	82.5	8944	.02756	14.909	22.385
9	Bare	0	67.2	11779	.03657	14.797	19.046
10	Bare	0	52.0	7483	.03542	9.706	10.744
11	Bare	0	36.8	4448	.03810	5.363	5.439

Run 1049

2	Cd	0	105.3	3119	.03524	3.947	
1	Cd	0	151.1	3220	.04045	3.552	
3	Cd	30.5	151.1	2856	.03385	3.762	
4	Cd	61.0	151.1	2782	.02793	4.401	
5	Cd	91.4	151.1	3820	.04173	4.082	
6	Cd	0	89.4	2030	.01730	5.232	
7	Cd	0	59.6	667	.04170	0.713	
8	Cd	0	29.1	18	.04210	0.019	
9	Bare	100.1	151.1	12652	.03648	15.465	22.219
10	Bare	115.4	151.1	10244	.03340	13.676	15.954
11	Bare	130.6	151.1	3483	.01610	9.646	9.932
12	Bare	145.8	151.1	2831	.01970	6.408	1.408

Run 1050

2	Cd	0	90.1	3510	.0391	3.381	
1	Cd	0	196.8	3042	.0380	3.015	
3	Cd	0	74.9	2236	.0341	2.470	
4	Cd	0	44.4	132	.0421	0.118	
5	Cd	107.7	151.1	1334	.0308	1.631	
6	Cd	138.2	151.1	52	.0348	0.056	

- (1) Observed activity corrected to shutdown time.
 (2) Specific activity is the disintegration per minute per gram at shutdown normalized for power to Run 1002.
 (3) Corrected for resonance integral effects due to differences in foil weights.

TABLE 11.3

Power Normalization Factors - Configuration 5A

<u>Run</u>	<u>Time</u>	<u>Decay Time (min)</u>	<u>Decay Factor</u>	<u>Activity (CPM)</u>	<u>Corrected Activity (CPM) (1)</u>	<u>Norm. Factor</u>
1047	1121.86	36.36	0.690	436627	301314	0.263
	1123.07	37.57	0.720	421934	303792	
	1124.27	38.77	0.740	407978	301904	
					<u>302337</u>	
1048	1031.08	36.11	0.685	424401	290715	0.272
	1032.38	37.41	0.720	408020	293774	
	1033.62	38.65	0.740	393726	291356	
					<u>291948</u>	
1049	1242.84	52.18	1.040	288666	300213	0.264
	1244.26	53.60	1.080	279443	301798	
	1245.51	54.85	1.110	272440	302408	
					<u>301473</u>	
1050	1440.79	29.82	0.551	648621	357390	0.223
	1442.25	31.28	0.575	614140	353131	
	1443.56	32.59	0.610	587495	358372	
					<u>356298</u>	

(1) Activity decay corrected to 50 min. after shutdown.

TABLE 11.4

Gold Foil Cadmium Ratios and Thermal Neutron Flux - Configuration 5A

Location		Bare	Cd	Cd Ratio	Corrected Cd Ratio	Thermal Flux	
Radial (cm)	Axial (cm)	d/m/gm $\times 10^{-5}$	d/m/gm $\times 10^{-5}$			A(1)	B(2)
0	44.4	7.5	0.118	55.08	25.90	2.46	0.584
0	59.6	12.2	0.713	16.55	7.42	3.82	0.669
0	74.9	16.0	2.470	6.48	3.39	4.53	0.788
0	89.4	10.0	5.232	1.91	1.53	1.66	1.000
0	90.1	9.228	3.381	2.73	1.52	1.44	0.947
0	105.3	6.122	3.947	1.55	1.23	0.70	- -
0	121.5	6.064	3.575	1.70	1.29	0.84	0.977
0	151.1	5.705	3.552	1.61	1.25	0.73	0.913
0	181.5	6.233	3.563	1.75	1.30	0.86	1.049
0	196.8	6.728	3.015	2.23	1.50	1.21	1.186
0	212.0	7.326	3.422	2.14	1.48	1.37	0.840
0	151.1	5.705	3.552	1.61	1.25	0.73	0.913
30.5	151.1	8.226	3.762	2.19	1.38	1.09	1.147
61.0	151.1	10.431	4.401	2.37	1.54	1.70	1.018
91.4	151.1	11.447	4.082	2.80	1.59	2.02	1.036
93.2	151.1	11.585	3.684	3.14	1.82	2.37	0.963
107.7	151.1	15.204	1.63	9.33	4.66	4.40	0.909
123.0	151.1	11.576	0.348	33.26	15.30	3.72	0.882
138.2	151.1	7.780	0.056	140.00	60.34	2.58	0.890
153.5	151.1	4.970	0.012	414.00	181.68	1.66	0.922
168.7	151.1	2.561	0.0022(3)	1164.00	513.20	0.85	0.966
183.9	151.1	0.408	0.0004(3)	1020.00	449.70	0.14	1.167
91.4	90.1	11.560	4.703	2.46	1.87	2.34	0.929
91.4	212.0	8.062	4.895	1.65	1.41	1.17	0.549

(1) Column A gives the thermal flux in $\text{n/cm}^2/\text{sec watt} \times 10^{-6}$ for Configuration 5.

(2) Column B is the ratio of thermal flux in Configuration 5 to Configuration 4.

(3) These are extrapolated values.

TABLE 11.5

Critical Fuel Tray Loading Arrangement - Configuration 5B

Tray No.	Number of Surfaces	Fuel Sheets per Tray (1)	Fuel Weight (2) (gm)
1	2	28	73.4
2	8	112	293.4
3	10	140	366.8
4	12	168	440.2
5	14	196	513.5
6	14	196	513.5
7	16	224	586.9
8	16	224	586.9
9	18	252	660.2
10	18	252	660.2
11	18	252	660.2
12	20	280	733.6
13	20	280	733.6
14	20	280	733.6
15	20	280	733.6
16	20	280	733.6
17	20	280	733.6
18	20	280	733.6
19	20	280	733.6
20	20	280	733.6
21	20	280	733.6
22	20	280	733.6
23	18	252	660.2
24	18	252	660.2
25	18	252	660.2
26	16	224	586.9
27	16	224	586.9
28	14	196	513.5
29	12	168	440.2
30	12	168	440.2
31	8	112	293.4
32	6	84	220.1
Totals	504	7056	18476.6

(1) Equivalent size 1.0 sheets of fuel

(2) Weights based on 2.62 gram per fuel sheet.

TABLE 11.6

Cadmium Ratios in Void Region - Configuration 5B - Reduced Loading

Foil No.	Type	Location	Activity CPM (1)	Foil Wt. (gm)	Specific Activity d/m/gm $\times 10^{-6}$ (2)	Corrected Cd Ratio
1	CF Cd	Next to D ₂ O	1915		.00192	
4	CF Bare	Next to D ₂ O	43728		.04373	22.83
3	CF Cd	Next to fuel	1898		.00190	
2	CF Bare	Next to fuel	38422		.03842	20.24
18	In Cd	Next to D ₂ O	9134	.00510	407.10	
19	In Bare	Next to D ₂ O	26696	.00679	893.70	1.90
12	In Cd	Next to fuel	9094	.00518	399.00	
21	In Bare	Next to fuel	18297	.00562	740.00	1.62
11	Au Cd	Next to D ₂ O	771	.0376	1.52	
14	Au Bare	Next to D ₂ O	2161	.0415	3.86	1.66
13	Au Cd	Next to fuel	768	.0408	1.39	
12	Au Bare	Next to fuel	1798	.0384	3.47	1.59
10	Au (Norm)	Normalizer	1681	.0335	3.72	
3	Mn Cd	Next to D ₂ O	660	.04267	2.07	
17	Mn Bare	Next to D ₂ O	9428	.04344	28.97	13.36
11	Mn Cd	Next to fuel	728	.04836	2.01	
10	Mn Bare	Next to fuel	7626	.04586	22.20	10.52

- (1) Observe activity corrected to 50 minutes after shutdown for catcher foils and to shutdown time for the remainder.
- (2) Specific activity is the disintegration per minute per gram at shutdown normalized for power to Run 1002.

TABLE 11.7

Cadmium Ratios in Void Region with 0.3175 cm Al and 1.2 cm Water

Foil No.	Type	Location	Activity CPM (1)	Foil Wt. (gm)	Specific Activity d/m/gm $\times 10^{-6}$ (2)	Corrected Cd Ratio
2	CF Cd	Next to D ₂ O	4757		.00476	
3	CF Bare	Next to D ₂ O	119711		.1197	25.17
4	CF Cd	Next to fuel	3619		.00362	
1	CF Bare	Next to fuel	67485		.0675	18.65
14	In Cd	Next to D ₂ O	21408	.00649	749.80	
11	In Bare	Next to D ₂ O	52772	.00584	2054.00	2.13
15	In Cd	Next to fuel	17049	.00515	752.50	
20	In Bare	Next to fuel	37250	.00519	1631.40	1.82
29	Au Cd	Next to D ₂ O	1467	.03900	2.79	
5	Au Bare	Next to D ₂ O	5388	.04173	9.56	2.01
28	Au Cd	Next to fuel	1494	.04310	2.57	
1	Au Bare	Next to fuel	3598	.04044	6.59	1.61
27	Au (Norm)	Normalizer	4107	.04140	7.35	
16	Mn Cd	Next to D ₂ O	5958	.04558	4.16	
5	Mn Bare	Next to D ₂ O	114869	.04448	82.25	18.82
23	Mn Cd	Next to fuel	5761	.04411	4.16	
19	Mn Bare	Next to fuel	70953	.04362	51.81	11.86

- (1) Observe activity corrected to 50 minutes after shutdown for catcher foils and to shutdown time for the remainder.
- (2) Specific activity is the disintegration per minute per gram at shutdown normalized for power to Run 1002.

Fig. 11.1 Radial power distribution from bare catcher foils at an axial position of 151.1 cm - configuration 5

Fig. 11.2 Axial power distribution from bare catcher foils at core center - configuration 5A

Fig. 11.3 Radial distribution of bare gold foil activity at an axial position of 151.1 cm - configuration 5

Fig. 11.4 Axial distribution of bare gold foil activity at the core center - configuration 5A

Fig. 11.5 Bare gold foil activity distribution in the reflector - configuration 5A

Fig. 11.6 Relative bare gold foil and wire data for the radial reflector - configuration 5A

Fig. 11.7 Gold cadmium ratios in the radial and end reflectors - configuration 5

Fig. 11.8 Thermal neutron flux distribution radially through axial center of core - configuration 5A

Fig. 11.9 Thermal neutron flux distribution axially through radial center of core - configuration 5A

12.0 CONFIGURATION 6

This configuration had the same fuel radius as Configurations 4 and 5 but the 10.16 cm thick beryllium segment in the reflector was moved back another 5 cm so that it was 10.8 cm from the cavity wall. This configuration was actually the one first tested after completing Configuration 3B reflector temperature coefficient of reactivity measurement and the fuel loading was as given in Table 7.4. Inserting 10.16 cm of beryllium in the D₂O required addition of fuel, as will be explained later. The exact number of sheets per surface along with the estimated total weights after the addition of fuel is given in Table 12.1.

12.1 Rod Worth and Reactivity Measurements

Prior to placing the beryllium in the radial reflector, some preliminary reactivity measurements were made on a single slab of beryllium about 40.64 cm wide. This slab was placed at the three anticipated beryllium positions, 0.8, 5.8 and 10.8 cm from the cavity wall. The following data were obtained:

<u>Slab Position from Cavity Wall</u>	<u>Reactivity Change %Δk</u>	<u>Extrapolated Worth of Total Ring of Be %Δk</u>
10.8 cm	-0.2111	-3.378
5.8 cm	-0.3097	-4.955
0.8 cm	-0.4786	-7.658

It will be observed that the measurement on the single piece of Be, which represents about 1/16 of the total, was lower than the full ring measurement in each case (Sections 10, 11 and below) but the data were useful in providing approximate values.

The base k-excess before placing any beryllium in the reflector was $2.783 \pm 0.083\% \Delta k$. This was based on a single measurement of total rod worth of $-4.260\% \Delta k$. The 3% standard error was assumed as a realistic value. After placing the beryllium in the reactor and adding 2701.1 grams of fuel, k-excess was $0.983 \pm 0.029\% \Delta k$ based on a measured total rod worth of $-4.374\% \Delta k$ (single measurement) and actuators 1 to 6 were equally withdrawn to 30.6 cm at delayed critical.

Fuel worth measurements were obtained at the center and outer edge of the fuel with the following results:

<u>Position</u>	<u>Fuel Worth %Δk/gm</u>
Core Center	$(0.656 \pm 0.086) \times 10^{-3}$
Outer edge of fuel	$(1.639 \pm 0.081) \times 10^{-3}$

The same procedure was used as with previous configurations to determine core average fuel worth from the power distribution data and the two measured fuel worths given above. The calculated core average was $(1.074 \pm 0.113) \times 10^{-3} \% \Delta k / \text{gm}$. The same value from Configuration 3B after building up k-excess for the moderator temperature coefficient measurement was $1.516 \times 10^{-3} \% \Delta k / \text{gm}$. The error on this value is uncertain but should be about the same as for Configuration 6. The average of the two values is $(1.295 \pm 0.113) \times 10^{-3} \% \Delta k / \text{gm}$. Using this plus the differences in k-excess gives the following worth of placing the Be at 10.8 cm from the cavity wall:

$$(0.983 \pm 0.029) - [(2.783 \pm 0.083) + 2701.1 \times (1.295 \pm 0.113) \times 10^{-3}] = -5.298 \pm 0.328 \% \Delta k$$

The subcritical data plus the base reactivity before placing the beryllium in the radial reflector gave a total loss in reactivity of $4.55 \% \Delta k$. This value probably has a 5 to 10% uncertainty. There is a 14% difference between this value and the one given above which is outside of the indicated experimental error. The subcritical data is considered to be less accurate.

Two separate rod worth measurements on Actuator 2 gave an average worth of $-0.764 \pm 0.026 \% \Delta k$. These measurements were obtained during the evaluation of a single beryllium block worth as a function of radial position in the radial reflector prior to placing the complete ring of beryllium in the D_2O .

12.2 Power Distribution Measurements - Bare Catcher Foils

Catcher foil measurements were made with fuel trays 1 and 32 (341 gm of fuel) out of the reactor to reduce k-excess. All control rods were withdrawn except actuator 6 which was nominally 11 cm withdrawn and the D_2O temperature was 29°C .

The measured power distribution data within the cavity based on bare catcher foils are given in Table 12.2 and Figures 12.1 and 12.2. The weighted average radial power was 1.375 compared to 1.398 for Configurations 4 and 1.359 for Configuration 5A. There were 2116 grams less fuel in the reactor for Configuration 6 including removal of trays 1 and 32, than for Configurations 4 and 5 in addition to the change in beryllium position. In spite of these changes, there was no appreciable difference in the weighted average radial for all three configurations. The relative power at the outer edge of the fuel was 2.10 for Configuration 6, 2.27 for Configuration 4 and 2.130 for Configuration 5. This would indicate very little change, if any, in radial power distribution in the core due to moving the beryllium in the range of 0.8 cm to 10.8 cm from the cavity wall.

The axial power distribution shown in Figure 12.2 gave an average of 1.191. This is 1.4% lower than the average for Configuration 4 and 0.5% higher than for Configuration 5A. The small differences are due primarily to an apparently bad data point at the separation plane (121.9 cm) on Configuration 6.

There were some foils exposed along the outer surface of the fuel during Run 1037. These were not intended as part of the principal axial power map for comparison purposes. These data were not plotted but are given in Table 12.2.

12.3 Resonance Detector Data - Gold Foils

12.3.1 Bare Gold Data

All of the gold foil data for this configuration are given in Table 12.3. These include both bare and cadmium covered foils. The data are power normalized to the same reference run (Run 1002) as all other gold data. The power normalization factors are given in Table 12.4. The absolute power level at the normalized power determined from the catcher foil data was 4.59 watts.

The relative radial and axial flux distributions obtained from the bare gold foils are presented in Figures 12.3 and 12.4. The weighted average radial within the fuel, normalized to the core center, was 1.221. This was 4.7% higher than for Configuration 4. The opposite was true of the catcher foil data; i.e., the relative power with respect to the core center for Configuration 6 was lower than Configuration 4. The difference was attributed primarily to the increase in fuel loading required for Configuration 4 which in turn causes a lower average flux in order to obtain the same total power. The actual difference between the two sets of gold data considered here was small and may be caused, in part, by data uncertainty. This is further substantiated after comparing the axial distribution from the gold data.

The axial flux profile given in Figure 12.4 shows an average value of 1.096. This is 2.5% lower than for Configuration 4. The points at the ends of the fueled region both decreased about 4.2% which is consistent with the catcher foil data. Although the radial flux profile from the gold foils within the cavity is not consistent with the axial results, it is concluded that shifting the beryllium from 9.8 cm to 10.8 cm from the cavity wall did not appreciably affect the flux distribution within the fueled region of the cavity, at least within the $\pm 2\%$ measurement uncertainty.

The profile of the gold foil activity within the radial and end reflectors is shown in Figure 12.5. The end reflector gave essentially the same results as noted for Configuration 4 except for a slightly higher flux over the peak region for this configuration. It will be noted that there were some points remeasured on repeat runs, which give a good indication of the repeatability of the gold data. The standard error was less than 3% which is considered to be acceptable for this type of measurement. The radial reflector showed a major change over previously observed flux patterns. The peak was shifted from about 15 cm to around 8 cm from the cavity wall and the normalized magnitude of the peak was increased 3.5% over Configuration 4 but was essentially the same as Configuration 3A. As a check on the foil measurements of radial flux distribution, a gold wire was exposed in the radial reflector. The wire and foil data are compared in Figure 12.6. As will be observed, the location of the peak was verified. The center of the

beryllium section was located at the normal flux peak (when no beryllium was in the reflector). It is evident that the beryllium is reflecting a large number of epithermal neutrons back towards the reactor after causing some energy degradation and that these neutrons are rapidly thermalized after re-entering the D_2O . Thus, the peak occurs about 3 cm toward the cavity from the beryllium. The bare foil activity in the radial reflector was consistently lower behind the beryllium than for Configuration 4. The better moderating and diffusing properties of heavy water result in a propensity for the flux to peak in it, rather than in the beryllium.

12.3.2 Cadmium Ratio

The gold foil cadmium ratios are shown in Table 12.5. The comparison between these results and Configuration 4 is also shown in Table 12.5. This comparison is for the region within the cavity. In all cases the ratio was higher for Configuration 6. Configuration 4 contained 1775 grams, 9.6%, more fuel than Configuration 6 in addition to the shift in beryllium position. The difference in fuel loading undoubtedly accounts for part of this difference in cadmium ratio within the core.

The cadmium ratio distributions in the reflectors are presented in Figure 12.7. The radial reflector showed a definite decrease in cadmium ratio compared to Configuration 4. The point nearest the cavity decreased 6.4%. Within the beryllium, the value was 25% lower than Configuration 4. Behind the beryllium, a generally lower cadmium ratio is also shown. Ignoring some of the data scatter and using the interpolated curves, there was a nominal 10% decrease compared to Configuration 4. This harder flux was apparently due to the location of beryllium in the radial reflector though data were not obtained in the outer 45.7 cm of the reflector. There does not seem to be any reason to expect a reversal in this region in the ratio between Configurations 4 and 6. This effect was reflected in the bare gold foil results which were consistently lower than observed for Configuration 4 for the same power level.

The cadmium ratios in the end reflector were essentially the same as observed before except near 61 cm where the point was low. The data uncertainty at this point was large because of the low net counts from the cadmium covered foil, 4 ± 2 counts per minute.

12.3.3 Thermal Neutron Flux Distribution - Gold Data

The calculated thermal neutron flux values from the gold foil data are given in Table 12.5, and Figures 12.8 and 12.9. This configuration is also compared with Configuration 4 in Table 12. . It will be noted that the center of the core shows a 20% difference, with Configuration 6 being the highest. Except for the end points in the end reflector, there was an average 4% decrease in thermal flux in the end reflector. The point at the control rod end of the core and the first point in the end reflector both show a higher thermal flux than Configuration 4 but this changes within the first 15 cm of the reflector and remains a fairly constant ratio, 0.96 ± 0.02 , of Configuration 4 the rest of the way out to the outer surface of the reflector, excluding

the last point which appears to be too high for this configuration. The point at the separation plane which shows a ratio to Configuration 4 of 1.02 was either unaffected by the configuration change or there was some unexpected error in the data on one of the sets of data.

The radial plot showed little change between Configurations 4 and 6 at the outer edge of the fuel, however, these data appear to contain some inconsistencies out to the edge of the cavity. Within the radial reflector there was a $17 \pm 6\%$ decrease in thermal flux, excluding the value at the outer edge of the reflector which appears to be in error on Configuration 4. This decrease agrees in general with the observed lower cadmium ratio results discussed in the previous section as well as the lower bare foil data in the radial reflector.

TABLE 12.1

Critical Fuel Tray Loading Arrangement - Configuration 6

Tray No.	Number of Surfaces	Fuel Sheets per Surface (1)	Fuel Weight (2) (gm)
1	2	32	83.8
2	8	120	314.4
3	10	145	379.9
4	12	183	479.5
5	14	229	600.0
6	14	210	550.2
7	16	232	607.8
8	16	235	615.7
9	18	261	683.8
10	18	270	707.4
11	18	261	683.8
12	20	303	793.9
13	20	290	759.8
14	20	300	786.0
15	20	290	759.8
16	20	303	793.9
17	20	290	759.8
18	20	300	786.0
19	20	290	759.8
20	20	303	793.9
21	20	290	759.8
22	20	300	786.0
23	18	261	683.8
24	18	273	715.3
25	18	269	704.8
26	16	241.5	632.7
27	16	232	607.8
28	14	210	550.2
29	12	174	455.9
30	12	183	479.5
31	8	125	327.5
32	6	98	256.8
Totals	504	7503.5	19659.3

(1) Number of equivalent size 1.0 fuel sheets

(2) Fuel weight based on average of 2.62 grams per fuel sheet

TABLE 12.2

Catcher Foil Data - Configuration 6

Run 1037

Foil No.	Type	Location		Tray No.	Normalized Counts (1)	Ratio of Local to Core Center (Foil No. X)
		Radial (cm)	Axial (cm)			
1	Bare	0	90.1	17	102127	1.980
2	Bare	0	106.3	17	67972	1.318
3	Bare	0	120.6	17	57033	1.106
4	Bare	0	135.8	17	53886	1.045
5	Bare	0	151.1	17	51572	1.000 (X)
6	Bare	0	166.3	17	53544	1.038
7	Bare	0	181.5	17	56508	1.096
8	Bare	0	196.8	17	65561	1.271
9	Bare	0	212.0	17	88418	1.714
10	Bare	61.0	120.1	17	121606	2.358
11	Bare	61.0	135.8	17	107871	2.092
12	Bare	61.0	151.1	17	105321	2.042
13	Bare	61.0	166.3	17	104691	2.030
14	Bare	61.0	181.5	17	98709	1.914
15	Bare	61.0	196.8	17	100317	1.945
16	Bare	61.0	212.0	17	103365	2.004

Run 1040

1	Bare	0	151.1	17	50805	1.000 (X)
2	Bare	15.2	151.1	17	50321	.990
3	Bare	30.5	151.1	17	58788	1.157
4	Bare	45.7	151.1	17	68364	1.345
5	Bare	61.0	151.1	17	106753	2.101
6	Bare	76.2	151.1	17	130404	2.566
7	Bare	91.4	151.1	17	133145	2.620

(1) Normalized to 100,000 counts on decay corrector.

TABLE 12.3
Gold Foil Data - Configuration 6

Foil No.	Type	Location		Activity (CPM) (1)	Foil Wt. (gm)	Specific Activity d/m/gm $\times 10^{-5}$ (2)
		Radial (cm)	Axial (cm)			
1	Bare	0	89.4	2053	.0188	11.085
2	Bare	0	74.9	3288	.0158	21.124
3	Bare	0	59.6	2773	.0158	17.815
4	Bare	0	44.4	1917	.0164	11.865
5	Bare	0	29.1	1289	.0175	7.477
6	Bare	0	13.9	615	.0164	3.807
7	Bare	0	0	85	.0146	5.901
8	Bare	93.2	151.1	1814	.0162	11.366
9	Bare	107.7	151.1	2358	.0162	14.775
10	Bare	123.0	151.1	1446	.0143	10.264
11	Bare	138.2	151.1	1417	.0202	7.121
12	Bare	153.5	151.1	841	.0177	4.823
13	Bare	168.7	151.1	362	.0145	2.534
14	Bare	182.8	151.1	136	.0186	0.742
15	Bare	0	90.1	1640	.0171	9.735
16	Bare	0	105.3	1257	.0160	7.975
17	Bare	0	120.6	1298	.0182	7.240
18	Bare	0	135.8	1246	.0177	7.146
19	Bare	0	151.1	1222	.0176	7.048
20	Bare	0	166.3	1164	.0161	7.339
21	Bare	0	181.5	1260	.0170	7.524
22	Bare	0	196.8	1229	.0151	8.262
23	Bare	0	212.0	1623	.0166	9.925

Run 1034

1	Cd	0	29.1	12	.0154	0.034
26	Bare	0	52.0	5388	.0159	14.824
25	Bare	0	67.2	7575	.0162	20.455
24	Bare	0	82.5	6662	.0156	18.681
2	Cd	153.5	151.1	4	.0134	0.013
29	Bare	130.6	151.1	3382	.0156	9.484
28	Bare	115.3	151.1	5385	.0178	13.234
27	Bare	100.1	151.1	6719	.0172	17.089
3	Cd	0	151.1	1673	.0145	5.047
4	Cd	30.5	151.1	2098	.0200	4.589
5	Cd	61.0	151.1	2169	.0205	4.628
6	Cd	91.4	151.1	2018	.0188	4.696

Run 1035

1	Cd	0	89.4	2184	.0190	4.892
2	Cd	0	44.4	76	.0187	0.173
3	Cd	93.2	151.1	2416	.0202	5.091
4	Cd	138.2	151.1	28	.0193	0.062

TABLE 12.3
(Continued)

Foil No.	Foil Type	Location		Activity (CPM) (1)	Foil Wt. (gm)	Specific Activity
		Radial (cm)	Axial (cm)			d/m/gm $\times 10^{-5}$ (2)
Run 1035 (Cont'd)						
5	Cd	0	90.1	1605	.0153	4.465
6	Cd	0	120.6	1738	.0172	4.301
7	Cd	0	151.1	1565	.0151	4.411
8	Cd	0	181.5	1881	.0185	4.328
9	Cd	0	212.0	2238	.0212	4.493
Run 1036						
1	Cd	0	59.6	356	.0147	1.035
2	Cd	0	29.1	16	.0212	0.032
3	Cd	123.0	151.1	162	.0163	0.425
4	Cd	153.5	151.1	8	.0169	0.020
5	Cd	0	135.8	1713	.0170	4.306
6	Cd	91.4	90.1	1866	.0213	3.744
7	Cd	91.4	212.0	1821	.0189	4.117
Run 1037						
10	Cd	107.7	151.1	1082	.0161	2.940
35	Bare	61.0	212.0	4330	.0167	11.342
36	Bare	61.0	196.8	4314	.0173	10.908
37	Bare	61.0	181.5	4260	.0178	10.469
38	Bare	61.0	166.3	3815	.0156	10.698
39	Bare	61.0	151.1	4107	.0171	10.506
40	Bare	61.0	135.8	4412	.0186	10.377
41	Bare	61.0	120.6	3835	.0156	10.754
42	Bare	91.4	212.0	4612	.0183	11.025
43	Bare	91.4	90.1	5177	.0198	11.438
Run 1038						
8	Cd	0	74.9	1854	.0200	3.867
12	Cd	123.0	151.1	1219	.0216	2.354
13	Bare	0	151.1	3222	.0212	6.340
14	Bare	15.2	151.1	2644	.0169	6.527
15	Bare	30.5	151.1	3189	.0186	7.153
16	Bare	45.7	151.1	3310	.0178	7.758
17	Bare	61.0	151.1	3532	.0148	9.956
18	Bare	76.2	151.1	4999	.0179	11.651
19	Bare	91.4	151.1	5131	.0187	11.447
30	Bare	0	52.0	6250	.0180	14.486
31	Bare	0	44.4	4621	.0153	12.600
32	Bare	0	29.1	2306	.0122	7.885
33	Bare	0	13.9	1729	.0186	3.878
34	Bare	0	0	232	.0176	0.550

TABLE 12.3
(Continued)

Foil No.	Foil Type	Location		Activity (CPM) (1)	Foil Wt. (gm)	Specific Activity
		Radial (cm)	Axial (cm)			d/m/gm $\times 10^{-5}$ (2)
Run 1039						
20	Cd	0	151.1	2002	.0211	4.054
22	Cd	45.7	151.1	1797	.0171	4.491
21	Cd	30.5	151.1	1909	.0193	4.227
23	Cd	61.0	151.1	1827	.0163	4.790
24	Cd	91.4	151.1	2058	.0177	4.968
Run 1040						
25	Bare	0	89.4	5115	.0221	9.968
26	Bare	0	74.9	9638	.0199	20.859
27	Bare	0	59.6	6549	.0159	17.740

(1) Observed activity corrected to shutdown time.

(2) Specific activity is the disintegration per minute per gram at shutdown normalized for power to Run 1002.

TABLE 12.4

Power Normalization Factors - Configuration 6

Run	Time	Decay Time (min)	Decay Factor	Activity (CPM)	Corrected Activity (CPM) (1)	Norm. Factor
1033	1434.16	21.19	0.420	320820	134744	0.601
	1435.56	22.59	0.435	303092	131845	
	1436.92	23.95	0.450	288659	129897	
					<u>132162</u>	
1034	1608.75	23.85	0.450	678740	305433	0.259
	1609.99	25.09	0.475	650486	308981	
	1611.32	26.42	0.490	622532	305041	
					<u>306485</u>	
1035	1116.05	23.75	0.450	698050	314122	0.252
	1117.30	25.00	0.475	667145	316894	
	1118.51	26.21	0.495	638646	316130	
					<u>315715</u>	
1036	1446.46	33.38	0.620	502213	311372	0.253
	1447.81	34.73	0.650	481954	313270	
	1449.06	35.98	0.680	464760	316037	
					<u>313560</u>	
1037	1605.42	16.62	0.335	918284	307625	0.259
	1606.68	17.88	0.350	867910	303768	
	1607.98	19.18	0.375	821334	308000	
					<u>306464</u>	
1038	1115.28	37.03	0.705	454303	320284	0.247
	1116.50	38.25	0.735	438379	322209	
	1117.72	39.47	0.760	424037	322268	
					<u>321587</u>	
1039	1447.36	22.08	0.425	739530	314300	0.253
	1448.57	23.29	0.445	707067	314645	
	1449.84	24.56	0.465	673410	313136	
					<u>314027</u>	
1040	1121.43	26.98	0.500	618898	309449	0.255
	1122.70	28.25	0.525	592777	311208	
	1123.96	29.51	0.550	568606	312733	
					<u>311130</u>	

(1) Activity decay corrected to 50 min. after shutdown.

TABLE 12.5

Gold Foil Cadmium Ratios and Thermal Neutron Flux - Configuration 6

Location		Bare	Cd	Cd Ratio	Corrected Cd Ratio	Thermal Flux	
Radial (cm)	Axial (cm)	d/m/gm $\times 10^{-5}$	d/m/gm $\times 10^{-5}$			A(1)	B(2)
0	0	0.591	0.0017(3)	348.00	201.00	0.20	1.11
0	13.9	3.81	0.0076(3)	529.00	289.00	1.25	0.96
0	29.1	7.48	0.0332	225.00	118.06	2.46	0.96
0	44.4	11.87	0.173	68.60	37.89	3.86	0.92
0	59.6	17.82	1.035	17.20	10.62	5.54	0.97
0	74.9	21.12	3.87	5.46	3.33	5.58	0.97
0	89.4	11.08	4.89	2.27	1.68	2.04	1.23
0	90.1	9.74	4.46	2.29	1.71	1.80	1.18
0	121.5	7.24	4.30	1.68	1.40	1.00	1.16
0	135.8	7.15	4.31	1.66	1.38	0.96	- -
0	151.1	7.05	4.41	1.60	1.38	0.94	1.18
0	181.5	7.52	4.33	1.74	1.39	1.01	1.23
0	212.0	9.92	4.49	2.21	1.58	1.66	1.02
0	151.1	7.05	4.41	1.60	1.38	0.94	1.18
30.5	151.1	7.15	4.23	1.69	1.37	0.94	0.99
45.7	151.1	7.75	4.49	1.73	1.42	1.10	- -
61.0	151.1	9.96	4.79	2.12	1.60	1.65	0.99
91.4	151.1	11.45	4.97	2.31	1.74	2.17	1.11
93.2	151.1	11.37	5.09	2.23	1.61	1.94	0.79
107.7	151.1	14.78	2.94	5.03	3.32	3.91	0.81
123.0	151.1	10.26	0.425	24.10	14.22	3.24	0.77
138.2	151.1	7.12	0.0618	115.20	62.67	2.33	0.81
153.5	151.1	4.82	0.0166	290.00	170.54	1.58	0.88
168.7	151.1	2.53	0.0042(3)	602.00	347.00	0.83	0.94
183.9	151.1	0.742	0.0012(3)	618.00	357.00	0.24	2.00
91.4	90.1	11.44	3.74	3.06	2.06	2.51	1.00
91.4	212.0	11.02	4.12	2.67	1.90	2.26	1.03

(1) Column A gives the thermal flux in $\text{n/cm}^2/\text{sec watt} \times 10^{-6}$ for Configuration 6

(2) Column B is the ratio of thermal flux in Configuration 6 to Configuration 4.

(3) Extrapolated values from existing gold foil data.

Fig. 12.1 Radial power distribution from bare catcher foils at an axial position of 151.1 cm - configuration 6

Fig. 12.2 Axial power distribution from bare catcher foils at core center - configuration 6

Fig. 12.3 Radial distribution of bare gold foil activity at an axial position of 151.1 cm - configuration 6

Fig. 12.4 Axial distribution of bare gold foil activity at the core center - configuration 6

Fig. 12.5 Bare gold foil activity distribution in the reflector - configuration 6

Fig. 12.6 Relative bare gold to lead activity in the radial reflector-configuration.

Fig. 12.7 Gold cadmium ratios in the radial and end reflectors - configuration 6

Fig. 12.8 Thermal neutron flux distribution radially through axial center of core - configuration 6

Fig. 12.9 Thermal neutron flux distribution axially through radial center of core - configuration 6

13.0 CONFIGURATION 7A

Configuration 7 required a variable fuel loading whereas all previous experiments involved a uniform distribution of fuel over the fueled region. The specification for Configuration 7A were as follows:

<u>Region No.</u>	<u>Diameter (cm)</u>	<u>Length (cm)</u>	<u>Relative Fuel Concentrations (mass/unit vol.)</u>	<u>Fractional Fuel Loading</u>
1	121.9	61.0	1.00	0.757
2	85.3	30.5	0.83	0.153
3	70.1	30.5	0.73	0.090

The final critical loading was almost identical with the distribution in the specifications.

In order to make this assembly critical, it was necessary to place 10,825 sheets of fuel in the reactor. The distribution of fuel was as shown in Figures 13.1, 13.2 and 13.3 for Regions 1, 2 and 3, respectively, and Table 13.1. The variation in number of sheets per surface was uniformly distributed over the fueled region. Region 1 was at the control rod end of the cavity, Region 2 in the center and Region 3 at the separation end of the cavity. The beryllium was at the same location as for Configuration 5 (5.8 cm from the cavity wall) for Configuration 7.

13.1 Rod Worth and Reactivity Measurements

Excess reactivity with the core fuel loading of 10,825 fuel (about 28.4 kg) was $1.57 \pm 0.08\% \Delta k$ based on a worth of Actuator 1 to 6 of $-4.8 \pm 0.2\% \Delta k$ and the rods 24.0 cm withdrawn. The change-over was made from Configuration 5A where k -excess was $3.098 \pm 0.093\% \Delta k$. The first estimate of the required fuel loading was about 8000 sheets or 21 kg of fuel. The upper 16 trays were changed and 3852 sheets of fuel added. Excess reactivity dropped to $0.266\% \Delta k$ or a net loss of $2.832\% \Delta k$. It was obvious at this point that more fuel would be necessary. The next estimate was for around 9500 fuel sheets, Trays 17 to 32 were changed to this new estimated loading and the reactor was about 2% subcritical. Extra fuel was added to trays 1, 2 and 32 to obtain criticality and some fuel worth measurements were made to help extrapolate the fuel loading requirements. The core center gave a fuel worth of $(0.33 \pm 0.11) \times 10^{-3} \% \Delta k / \text{gm}$ and at the edge of the core the fuel worth was $(0.88 \pm 0.23) \times 10^{-3} \% \Delta k / \text{gm}$. From these measurements, it was determined that between 10,000 and 11,000 sheets of fuel would probably provide a critical mass with adequate k -excess.

A single rod worth measurement on Actuator 6 gave a worth of $-0.786\% \Delta k$ which was about 7% higher than for Configuration 3A. A single measurement on Actuator 1 to 6 gave a worth of $-5.022\% \Delta k$ which appeared to be high. Later measurements on Configuration 7 gave values near $-4.8\% \Delta k$

and for this reason the final k-excess given above was based on this value. The rod worths were definitely higher than for Configuration 3A because of the heavy fuel loading in the end of the reactor where the control rods were located.

13.2 Power Distribution Measurements

13.2.1 Bare Catcher Foils

Bare catcher foil data were obtained at the center of each region, at the transition region between each region, and at the separation plane. A complete axial power profile at the core center was also measured. All of the catcher foil data are given in Table 13.2. These measurements were made with the rods on Actuators 1 to 6 withdrawn about 25 cm and the D_2O at $26^\circ C$. The radial profiles at the six positions are shown in Figures 13.4, 13.5 and 13.6. The weighted averages out to the edge of the fuel are summarized as follows:

<u>Location</u>	<u>Weight Average</u>	<u>Peak at Outer Edge of Fuel</u>
Center of Region 1	1.340	2.71
Between Regions 1 and 2	2.133	3.27
Center of Region 2	1.618	2.70
Between Regions 2 and 3	2.137	3.13
Center of Region 3	1.580	2.95
Separation Plane	2.925	3.48

The weighted average between each region is based on the fuel diameter of the largest region. It will be noted that the radials in Region 3 both show an increase in power at the radial center compared to 15.2 cm from the center. This is believed to be due to the flux peak in the 30.5 cm diameter hole in the end reflector.

The axial power profile is given in Figure 13.7. Included in this figure are the points at the outer surface of the fuel. As would be expected, there are discontinuities between each of the regions at the outer edge of fuel. The axial power profile at the core center shows a minimum point at or near the center of Region 1, which contains the heaviest fuel loading. The average of the curve at the radial center of the core was 1.183.

13.2.2 Cadmium Ratio

Sufficient cadmium covered catcher foils were exposed in the cavity to obtain a radial at the center of each region, an axial at the radial center and the points in the corner of the cavity at each end of the cavity. The results are shown in Table 13.3. The radial distribution at the center of each region is given in Figure 13.8. As would be expected,

the cadmium ratio increased as the regional loading decreased. At the outer edge of the fueled regions there was little difference in the cadmium ratios which varied from 16.5 to 17.7.

The axial cadmium ratio distribution at the core center is presented in Figure 13.9. These data appear to be consistent with power distribution results.

TABLE 13.1

Critical Fuel Tray Loading Arrangement - Configuration 7A

Region 1			
Tray No.	Number of Surfaces	Fuel Sheets per Tray (1)	Fuel Weight (2) (gm)
1	2	32	83.8
2	8	130	340.6
3	10	163	427.1
4	12	196	513.5
5	14	228	597.4
6	14	228	597.4
7	16	260	681.2
8	16	260	681.2
9	18	292	765.0
10	18	293	767.7
11	18	292	765.0
12	20	325	851.5
13	20	325	851.5
14	20	325	851.5
15	20	325	851.5
16	20	325	851.5
17	20	325	815.5
18	20	325	851.5
19	20	325	851.5
20	20	325	851.5
21	20	325	815.5
22	20	325	851.5
23	18	293	767.7
24	18	292	765.0
25	18	293	767.7
26	16	260	681.2
27	16	260	681.2
28	14	229	600.0
29	12	195	510.9
30	12	195	510.9
31	8	131	343.2
32	6	98	256.8
Totals	504	8195	21470.9
Region 2			
6	2	13	34.1
7	6	39	102.2
8	8	52	136.2
9	10	65	170.3
10	12	78	204.4
11	12	78	204.4
12	12	78	204.4
13	14	91	238.4

TABLE 13.1
(Continued)

Region 2 (Cont'd)			
Tray No.	Number of Surfaces	Fuel Sheets per Tray (1)	Fuel Weight (2) (gm)
14	14	93	243.7
15	14	91	238.4
16	14	91	238.4
17	14	91	238.4
18	14	91	238.4
19	14	91	238.4
20	14	93	243.7
21	14	92	241.0
22	12	78	204.4
23	12	78	204.4
24	12	78	204.4
25	10	65	170.3
26	8	52	136.2
27	8	52	136.2
28	4	26	68.1
Totals	254	1656	4338.8
Region 3			
8	2	11	28.8
9	6	34	89.1
10	8	46	120.5
11	8	46	120.5
12	10	58	152.0
13	10	56	146.7
14	10	57	149.3
15	12	70	183.4
16	12	70	183.4
17	12	68	178.2
18	12	68	178.2
19	12	69	180.8
20	10	57	149.3
21	10	57	149.3
22	10	57	149.3
23	8	47	123.1
24	8	46	120.5
25	6	34	89.1
26	4	23	60.3
Totals	170	974	2551.8

(1) Equivalent size 1.0 fuel sheets

(2) Based on 2.62 gm per fuel sheet

TABLE 13.2
Catcher Foil Data - Configuration 7A

Run 1051

Foil No.	Type	Location		Tray No.	Normalized Counts (1)	Ratio of Local to Core Center (Foil No. X)
		Radial (cm)	Axial (cm)			
1	Cd	0	90.1	17	5405	
2	Cd	0	120.6	17	5201	
3	Cd	0	166.3	17	4951	
4	Cd	0	196.8	17	6196	
5	Cd	42.7	166.3	17	5925	

Run 1052

1	Cd	91.4	212.0	17	4696	0.132
5	Cd	30.5	120.6	17	4975	0.139
4	Cd	61.0	120.6	17	5786	0.162
2	Cd	91.4	120.6	17	6350	0.180
54	Cd	91.4	90.1	17	5574	0.156
3	Bare	91.4	90.1	17	148955	4.173
6	Bare	0	212.0	17	106527	2.984
7	Bare	0	196.8	17	61593	1.726
8	Bare	0	181.5	17	45502	1.275
9	Bare	0	166.3	17	40052	1.122
10	Bare	0	151.1	17	35686	1.000 (X)
11	Bare	0	135.8	17	31452	0.881
12	Bare	0	120.6	17	24504	0.687
13	Bare	0	105.3	17	33172	0.929
14	Bare	0	90.1	17	63756	1.786
6	Bare	0	212.0	17	106527	2.984
15	Bare	15.2	212.0	17	97743	2.738
21	Bare	30.5	212.0	17	109929	3.080
27	Bare	35.1	212.0	17	123715	3.466
30	Bare	42.7	212.0	17	133841	3.750
36	Bare	61.0	212.0	17	141010	3.951
42	Bare	76.2	212.0	17	144875	4.059
48	Bare	91.4	212.0	17	133182	3.731
7	Bare	0	196.8	17	61593	1.726
16	Bare	15.2	196.8	17	50098	1.404
22	Bare	30.5	196.8	17	76304	2.138
28	Bare	35.1	196.8	17	104650	2.932

TABLE 13.2
(Continued)Run 1052 (Cont'd)

Foil No.	Type	Location		Fray No.	Normalized Counts (1)	Ratio of Local to Core Center (Foil No. X)
		Radial (cm)	Axial (cm)			
31	Bare	42.7	196.8	17	117723	3.298
37	Bare	61.0	196.8	17	128717	3.606
43	Bare	76.0	196.8	17	142976	4.006
49	Bare	91.4	196.8	17	139114	3.897
8	Bare	0	181.5	17	45502	1.275
17	Bare	15.2	181.5	17	61557	1.725
23	Bare	30.5	181.5	17	68335	1.914
29	Bare	35.1	181.5	17	89056	2.495
32	Bare	42.7	181.5	17	113206	3.172
38	Bare	61.0	181.5	17	131822	3.693
44	Bare	76.2	181.5	17	136278	3.818
50	Bare	91.4	181.5	17	139546	3.910
18	Bare	15.2	166.3	17	42672	1.196
24	Bare	30.5	166.3	17	54093	1.515
33	Bare	42.7	166.3	17	97879	2.742
39	Bare	61.0	166.3	17	125002	3.502
45	Bare	76.2	166.3	17	133281	3.734
51	Bare	91.4	166.3	17	140561	3.938
10	Bare	0	151.1	17	35686	1.000 (X)
19	Bare	15.2	151.1	17	37066	1.038
25	Bare	30.5	151.1	17	45746	1.282
34	Bare	42.7	151.1	17	76197	2.135
40	Bare	61.0	151.1	17	118900	3.331
46	Bare	76.2	151.1	17	103587	3.659
52	Bare	91.4	151.1	17	138352	3.876
12	Bare	0	120.6	17	24504	0.687
20	Bare	15.2	120.6	17	27294	0.765
26	Bare	30.5	120.6	17	31246	0.868
35	Bare	42.7	120.6	17	37147	1.041
41	Bare	61.0	120.6	17	98467	2.758
47	Bare	76.2	120.6	17	127523	3.573
53	Bare	91.4	120.6	17	133357	3.739

Run 1053

1	Cd	42.7	120.6	17	5119
2	Cd	15.2	196.8	17	5121
3	Cd	0	212.0	17	5643
4	Cd	15.2	166.3	17	5289
5	Cd	35.1	196.8	17	5925

(1) Normalized to 100,000 counts on decay corrector.

TABLE 13.3

Catcher Foil Cadmium Ratios - Configuration 7A

Run No.	Location Radial Axial (cm) (cm)		Tray No.	Normalized Bare Foil Activity	Normalized Cd Foil Activity	Cd Ratio Bare/Cd Activity
1052,1051	0	90.1	17	63756	5405	11.80
1052,1051	0	120.6	17	24504	5201	4.71
1052,1051	0	166.3	17	40052	4951	8.09
1052,1051	0	196.8	17	61593	6196	9.94
1052,1053	0	212.0	17	106527	5643	18.88
1052,1051	0	120.6	17	24504	5201	4.71
1052,1052	30.5	120.6	17	30996	4975	6.23
1052,1053	42.7	120.6	17	37147	5119	7.26
1052,1052	61.0	120.6	17	98433	5786	17.01
1052,1052	91.4	120.6	17	133446	6350	21.02
1052,1051	0	166.3	17	40052	4951	8.09
1052,1053	15.2	166.3	17	42672	5289	8.07
1052,1051	42.7	166.3	17	97879	5925	16.52
1052,1051	0	196.8	17	61593	6196	9.94
1052,1053	15.2	196.8	17	50098	5121	9.78
1052,1053	35.1	196.8	17	104650	5925	17.66
1052,1052	91.4	212.0	17	133182	4696	28.36
1052,1052	91.4	90.1	17	148955	5574	26.73

373 Surfaces with 16 Sheets per Surface
 131 Surfaces with 17 Sheets per Surface
 Total - 8195 Sheets

Fig. 13.1 Fuel tray installation pattern - configuration 7A - region 1

132 Surfaces with 7 Sheets per Surface
 122 Surfaces with 6 Sheets per Surface
 Total - 1656 Sheets

Fig. 13.2 Fuel tray installation pattern - configuration 7A - region 2

124 Surfaces with 6 Sheets per Surface
 46 Surfaces with 5 Sheets per Surface
 Total - 974 Sheets

Fig. 13.3 Fuel tray installation pattern - configuration 7A - region 3

Fig. 13.4 Radial power distribution from bare catcher foils - configuration 7A

Fig. 13.5 Radial power distribution from bare catcher foils - configuration 7A

Fig. 13.6 Radial power distribution from bare catcher foils - configuration 7A

Fig. 13.7 Axial power distribution for temperature distribution configuration 7A

Fig. 13.8 Catcher foil cadmium ratio radial profiles - configuration 7A

Fig. 13.9 Catcher foil cadmium ratio axial profile at radial center - configuration 7A

14.0 CONFIGURATION 7B

This assembly consisted of two fuel regions with varied fuel loadings. Each region was 61.0 cm long. The first 61.0 cm from the end of the core containing rods (Region 1) was to have a relative fuel density of 1.0 compared to 0.54 for the other half of the cavity (Region 2). The fuel diameter in the control rod end of the core was 121.9 cm while the other section was 110.0 cm in diameter. The calculated total fraction of fuel required in Region 1 was 0.695 and in Region 2 was 0.305. The actual fuel distribution attained at criticality was 0.649 of the fuel in Region 1 and 0.351 of the fuel in Region 2. This gives a relative fuel density of 0.667 for Region 2 compared to 1.0 for Region 1. The exact fuel arrangement for each region is shown in Figures 14.1, 14.2 and Table 14.1. No attempt was made to redistribute the fuel to exactly the specified relative concentrations.

14.1 Rod Worth and Reactivity Measurements

The initial estimate of the fuel loading requirements for this configuration was about 20.5 kg. This proved to be a valid estimate as k -excess was $0.245 \pm 0.012\% \Delta k$ with the core loaded with 20.3 kg of Orallo. This was based on a single measured worth of Actuator 1 to 7 of $-5.25 \pm 0.26\% \Delta k$ and all rods withdrawn 32.6 cm. The standard deviation was assumed to be 5%. The worth of Actuator 6 was measured to be $-0.790 \pm 0.027\% \Delta k$ which is 9.4% higher than for Configuration 3A. This increase in rod worth due to a heavy fuel loading in the front of the reactor is consistent with results obtained for Configuration 7A.

14.2 Power Distribution Measurements

14.2.1 Bare Catcher Foil

The power distribution data within the cavity were obtained with both bare and cadmium covered catcher foils. The rods were withdrawn except Actuators 4, 5 and 6 which were 40.9 cm withdrawn and the D_2O temperature was $24^\circ C$. Bare foils were exposed at the center and ends of each section to obtain radial power profiles. In addition, a complete axial power map at the radial center of the core was measured. These data are found in Table 14.2. Included here are also the cadmium covered foil data. The bare foil results are shown graphically in Figures 14.3 to 14.5. The weighted averages for these curves over the fueled regions are summarized below:

<u>Location</u>	<u>Weight Average</u>
At end of Region 1 - 90.0 cm from end of core	1.969
At center of Region 1 - 120.6 cm from end of core	1.247
At end of Region 1 - 151.1 cm from end of core	1.413
At center of Region 2 - 181.5 cm from end of core	1.546
At separation plane, end of Region 2 - 212.0 cm from end of core	2.093

The axial power profile is given in Figure 14.5. The minimum power occurred near the center of Region 1 which contains the heavy fuel loading. The curve average was 1.139 which is only 3.7% lower than for Configuration 7A. The general curve shapes for the two configurations were much the same with Configuration 7A showing more severe gradients because of the heavier and more varied fuel loading.

14.2.2 Cadmium Ratios

Sufficient cadmium covered foils were exposed to produce radials at the center of each region and an axial at the core center. The values obtained are given in Table 14.3. The two radials and axial are shown in Figures 14.6 and 14.7. It will be noted that the cadmium covered foil for the point at a radial distance of 54.9 cm and axial distance of 181.5 cm was lost. A value of 6000 counts, consistent with all the other foils in this region, was assumed.

The resulting cadmium ratio shown on Figure 14.6 appears to be in line with the other data.

Compared to Configuration 7A, there was no measureable change in the cadmium ratio at the outer edge of the fuel in Region 1, at the separation plane or in the corners of the cavity. The only changes occurred in the central region of the core where the lighter fuel loading in Configuration 7B resulted in less thermal flux absorption and higher cadmium ratios than for Configuration 7A.

14.3 Neutron Lifetime Measurements

Neutron lifetime measurements were made as in Configuration 7B. Data were obtained at three subcritical levels; $-5.2\%\Delta k$, $-2.0\%\Delta k$ and $-1.0\%\Delta k$. The subcritical levels were based on measured rod worths and should be accurate to a standard error of 5% or less. Three different pulsing rates and channel widths were tried, two of which proved to give consistent results. The results are given in Table 14.4. It will be noted that the pulse rates reported were 0.67 and 2 per second. The other pulse rate was 10 per second but it was found that the data did not agree well with the lower pulse rates and there were always larger errors associated with the data. A close examination of the data indicated too high a pulse rate does not allow sufficient decay with respect to the background level before the next pulse is introduced. The overall weighted average lifetime was $(3.48 \pm 0.06) \times 10^{-3}$ sec. The standard error includes only the observed variation in alpha. Uncertainties in reactivity values were not included, since these were nominally much less than the curve fit uncertainties.

The neutron lifetime with beryllium in the reflector was about 12% above the value without beryllium as Configuration 3B gave a lifetime of 3.10×10^{-3} sec. There were, of course, major fuel changes between these two configurations as well as the addition of beryllium in the radial reflector. The increase in fuel loading of about 3.3 kg (16%) in this configuration compared to Configuration 3B would, in and of itself, cause a decreased or shorter neutron lifetime. Therefore, the addition of 10.16 cm beryllium around the cavity at 5.8 cm from the cavity wall

apparently increased the neutron lifetime. It will be shown later that a 20% increase in fuel loading poisoned down with boron caused a 26.4% decrease in neutron lifetime. Thus, the beryllium plus the slightly reduced fuel diameter in Region 2 may have been responsible for an increased effect on the neutron lifetime of as much as 25% assuming no fuel had been added to the reactor.

TABLE 14.1

Critical Fuel Loading Arrangement - Configuration 7B

Region 1			
Tray No.	Number of Surfaces	Fuel Sheets per Tray (1)	Fuel Weight (2) (gm)
1	2	20	52.4
2	8	80	209.6
3	10	100	262.0
4	12	120	314.4
5	14	140	366.8
6	14	140	366.8
7	16	160	419.2
8	16	160	419.2
9	18	180	471.6
10	18	180	471.6
11	18	180	471.6
12	20	200	524.0
13	20	200	524.0
14	20	200	524.0
15	20	200	524.0
16	20	200	524.0
17	20	200	524.0
18	20	200	524.0
19	20	200	524.0
20	20	200	524.0
21	20	200	524.0
22	20	200	524.0
23	18	180	471.6
24	18	180	471.6
25	18	180	471.6
26	16	160	419.2
27	16	160	419.2
28	14	140	366.8
29	12	120	314.4
30	12	120	314.4
31	8	80	209.6
32	6	60	157.2
Totals	504	5040	13204.8
Region 2			
3	4	26	68.1
4	8	54	141.5
5	10	66	172.9
6	12	79	207.0
7	12	80	209.6
8	14	93	243.7
9	16	107	280.3
10	16	107	280.3

TABLE 14.1
(Continued)

Region 2 (Cont'd)			
Tray No.	Number of Surfaces	Fuel Sheets per Tray (1)	Fuel Weight (2) (gm)
11	16	106	277.7
12	16	107	280.3
13	18	121	317.0
14	18	119	311.8
15	18	120	314.4
16	18	119	311.8
17	18	120	314.4
18	18	120	314.4
19	18	119	311.8
20	18	119	311.8
21	18	120	314.4
22	16	107	280.3
23	16	106	277.7
24	16	107	280.3
25	16	106	277.7
26	14	93	243.7
27	12	80	209.6
28	12	80	209.6
29	10	66	172.9
30	8	53	138.9
31	4	26	68.1
Totals	410	2726	7142.0

(1) Equivalent size 1.0 sheets

(2) Based on 2.62 gm per fuel sheet

TABLE 14.2
Catcher Foil Data - Configuration 7B

Foil No.	Type	Location		Tray No.	Normalized Counts (I)	Ratio of Local to Core Center (Foil No. X)
		Radial (cm)	Axial (cm)			
1	Cd	91.4	212.0	17	4901	0.096
2	Cd	91.4	120.6	17	6218	0.121
4	Cd	61.0	120.6	17	5973	0.116
5	Cd	30.5	120.6	17	5583	0.109
3	Bare	91.4	90.1	17	149572	2.917
6	Bare	0	212.0	17	106021	2.068
7	Bare	0	196.8	17	71805	1.400
8	Bare	0	181.5	17	59638	1.163
9	Bare	0	166.3	17	56559	1.103
10	Bare	0	151.1	17	51273	1.000 (X)
11	Bare	0	135.8	17	46142	0.900
12	Bare	0	122.6	17	45586	0.889
13	Bare	0	185.3	17	54529	1.063
14	Bare	0	90.1	17	82934	1.617
15	Bare	15.2	212.0	17	97057	1.893
20	Bare	30.5	212.0	17	96632	1.885
25	Bare	45.7	212.0	17	114365	2.231
30	Bare	54.9	212.0	17	128349	2.503
33	Bare	61.0	212.0	17	135031	2.634
38	Bare	76.2	212.0	17	138619	2.703
42	Bare	91.4	212.0	17	132639	2.587
16	Bare	15.2	181.5	17	60723	1.184
21	Bare	30.5	181.5	17	63798	1.244
26	Bare	45.7	181.5	17	81062	1.581
31	Bare	54.9	181.5	17	107206	2.091
34	Bare	61.0	181.5	17	121782	2.375
39	Bare	76.2	181.5	17	137698	2.686
43	Bare	91.4	181.5	17	135505	2.643
17	Bare	15.2	151.1	17	50619	0.987
22	Bare	30.5	151.1	17	57403	1.120
27	Bare	45.7	151.1	17	72460	1.413
32	Bare	54.9	151.1	17	91537	1.785
35	Bare	61.0	151.1	17	106721	2.081
40	Bare	76.2	151.1	17	136338	2.659
44	Bare	91.4	151.1	17	134595	2.625
18	Bare	15.2	120.6	17	47800	0.932
23	Bare	30.5	120.6	17	49791	0.971
28	Bare	45.7	120.6	17	61463	1.199
36	Bare	61.0	120.6	17	102955	2.008
41	Bare	76.2	120.6	17	135049	2.634

TABLE 14.2
(Continued)Run 1057 (continued)

Foil No.	Type	Location		Tray No.	Normalized Counts (1)	Ratio of Local to Core Center (Foil No. X)
		Radial (cm)	Axial (cm)			
44	Bare	91.4	151.1	17	134595	2.625
18	Bare	15.2	120.6	17	47800	.932
23	Bare	30.5	120.6	17	49791	.971
28	Bare	45.7	120.6	17	61463	1.199
36	Bare	61.0	120.6	17	102955	2.008
41	Bare	76.2	120.6	17	135049	2.634
45	Bare	91.4	120.6	17	134759	2.628
19	Bare	15.2	90.1	17	82264	1.604
24	Bare	30.5	90.1	17	85898	1.672
29	Bare	45.7	90.1	17	103636	2.021
37	Bare	61.0	90.1	17	126142	2.460
46	Cd	91.4	90.1	17	5361	.105

Run 1058

1	Cd	30.5	181.5	17	5465
2	Cd	0	181.5	17	5308
3	Cd	0	120.6	17	5404
4	Cd	45.7	181.5	17	5880
5	Cd	91.4	181.5	17	5997

Run 1059

1	Cd	30.5	181.5	17	5735
2	Cd	0	212.0	17	5507
3	Cd	0	151.1	17	5529
4	Cd	0	90.1	17	6293
5	Cd	45.7	120.6	17	5811
6	Cd	54.9	181.5	17	0

(1) Normalized to 100,000 counts on decay correctors.

TABLE 14.3
Catcher Foil Cadmium Ratios - Configuration 7B

Run No.	Location		Tray No.	Normalized Bare Foil Activity	Normalized Cd Foil Activity	Cd Ratio Bare/Cd Activity
	Radial (cm)	Axial (cm)				
1057,1059	0	90.1	17	82934	6293	13.18
1057,1058	0	120.6	17	45586	5404	8.44
1057,1059	0	151.1	17	51273	5529	9.27
1057,1058	0	181.5	17	59638	5308	11.24
1057,1059	0	212.0	17	106021	5507	19.25
1057,1058	0	181.5	17	59638	5308	11.24
1057,1059	30.5	181.5	17	63798	5601	11.39
1057,1058	45.7	181.5	17	81062	5880	13.79
1057,1059	54.9	181.5	17	107206	(6000 est.)	17.90
1057,1058	91.4	181.5	17	135505	5997	22.59
1057,1058	0	120.6	17	45586	5404	8.44
1057,1057	30.5	120.6	17	49791	5583	8.92
1057,1059	45.7	120.6	17	61463	5811	10.58
1057,1057	61.0	120.6	17	102955	5973	17.24
1057,1057	91.4	120.6	17	134759	6218	21.67
1057,1057	91.4	90.1	17	149572	5361	27.90
1057,1057	91.4	212.0	17	132639	4901	27.06

TABLE 14.4

Neutron Lifetime Measurements - Configuration 7B

Run No.	Channel Width (m sec)	Pulse Rate (sec ⁻¹)	Subcritical Level (% Δk)	Bkg. (CPM)	Intercept (CPM)	Alpha (sec ⁻¹)	± Error on Alpha (sec ⁻¹)
7-1	5.12	0.67	5.2 ± .2	419	1066	-17.82	0.30
7-2	5.12	0.67	5.2 ± .2	780	773	-15.95	0.45
7-3	1.28	2.0	5.2 ± .2	320	1112	-16.61	0.27
7-4	1.28	2.0	5.2 ± .2	259	1918	<u>-18.38</u>	0.22
						-17.58 ± 0.14 (1)	
7-18	5.12	0.67	1.0 ± .02	1284	854	-5.04	0.09
7-19	5.12	0.67	1.0 ± .02	1250	857	-5.11	0.09
7-7	1.28	2.0	1.0 ± .02	1925	123	-5.60	0.94
7-8	1.28	2.0	1.0 ± .02	1098	950	-3.91	0.19
7-9	1.28	2.0	1.0 ± .02	1082	988	<u>-3.67</u>	0.19
						-4.89 ± 0.06	
7-15	5.12	0.67	2.0 ± .04	807	1344	-8.01	0.11
7-16	5.12	0.67	2.0 ± .04	807	1338	-8.15	0.10
7-13	1.28	2.0	2.0 ± .04	601	1473	-7.40	0.14
7-14	1.28	2.0	2.0 ± .04	616	1484	<u>-7.59</u>	0.13
						-7.87 ± 0.06	

$$\ell = \frac{(.00765 \times 6.80 \times .958) + (.00765 \times .958)}{17.58 \pm 0.14} = 3.22 \pm .14$$

$$\ell = \frac{(.00765 \times 1.31 \times .99) + (.00765 \times .99)}{4.89 \pm 0.06} = 3.61 \pm .08$$

$$\ell = \frac{(.00765 \times 2.61 \times .98) + (.00765 \times .98)}{7.87 \pm 0.06} = 3.44 \pm .07$$

$$\text{Weighted Average} \quad 3.48 \pm 0.06$$

(1) All errors for results at a given subcritical level are assumed to be purely statistical counting uncertainties.

Fixed Table

504 Surfaces with 10 Sheets per Surface
Total - 5040 Sheets

Fig. 14.1 Fuel tray installation pattern - configuration 7B - region 1

266 Surfaces with 7 Sheets per Surface
 144 Surfaces with 6 Sheets per Surface
 Total - 2726 Sheets

Fig. 14.2 Fuel tray installation pattern - configuration 7B - region 2

Fig. 14.3 Radial power distribution from bare catcher foils - configuration 7B

Fig. 14.4 Radial power distribution from bare catcher foils - configuration 7B

Fig. 14.5 Axial power distribution from bare catcher foils - configuration 7B

Fig. 14.6 Catcher foil cadmium ratio radial profiles - configuration 7B

Fig. 14.7 Catcher foil cadmium ratio axial profile at radial center - configuration 7B

15.0 CONFIGURATION 7C

The only change between this configuration and Configuration 7A was in Region 3. This region was moved over so that one edge was lined up with the outer edge of Region 2. The fuel was effectively moved over one fuel surface (about 6.1 cm) as shown in Figure 15.1.

15.1 Rod Worth and Reactivity Measurements

The off-center shift of Region 3, as described above, caused an increase in reactivity of $0.059 \pm 0.005\% \Delta k$. This was based on the average of two rod worth measurements for Actuators 1 to 6 of $-4.794 \pm 0.015\% \Delta k$ and the rods 23.4 cm withdrawn. Note, this positive change from the fuel shifting is opposite to the effect observed with off-center shifting of the uniformly-loaded Configuration 5B.

15.2 Power Distribution Measurements

15.2.1 Bare Catcher Foils

Essentially the same measurements were made on this configuration as for Configuration 7A. Actuator 7 was withdrawn and Actuators 1 to 6 were 23.6 cm withdrawn. The D_2O temperature was nominally $24^\circ C$ during the power distribution measurements. The power mapping in Region 3 was from the center of the core to the outer edge of the fuel which lined up with Region 2 and to the opposite edge of Region 3. The catcher foil data are given in Table 15.1. This table includes both the bare and cadmium covered foil data.

The radial power profiles are shown in Figures 15.2 to 15.5. The weighted radial averages compare with Configuration 7A as follows:

<u>Location</u>	<u>Weight Average Config. 7A</u>	<u>Weight Average Config. 7C</u>	<u>Ratio Config. 7C/ Config. 7A</u>
Center of Region 1	1.340	1.305	0.904
Between Regions 1 and 2	2.133	1.918	0.899
Center of Region 2	1.618	1.499	0.926
Between Regions 2 and 3	2.137	1.813	0.848
Center of Region 3 *	1.945	2.038	1.048
Separation Plane *	2.925	2.702	0.924

* In the direction toward which Regions 2 and 3 are tangent to each other.

There was a general decrease in relative power with respect to the core center in all of the radial profiles except the one at the center of Region 3 which shows an increase of 4.8%. There was some data uncertainty in the radial profile for Configuration 7A which may account for some of this difference. The point at the outer edge of the fuel was virtually unchanged in Region 3. The difference was mainly over the central region where the uncertainty occurred. The decrease over the outer portion of the other radials was apparently due to the extra neutron absorption in the outer surface of Region 3 which was lined up with Region 2. A radial profile across the core, 180 degrees from the plotted radials, was not measured. There were, however, three foils on the opposite side of the cavity in Region 3 as shown in Figure 15.5. Comparing these three points for Configuration 7A, shows a general decrease. The point nearest Region 2 decreased 32%. The point at the center of Region 3 only decreased 1.7% while the point at the separation plane decreased 8.3%. The large decrease next to Region 2 was due to the increased shadowing from Region 2. The odd distribution shown in Figure 15.5 at 212.0 cm was caused by the 30.5 cm void region in the end reflector.

The axial power distribution is given in Figure 15.6. The average of the curve at the radial center of the core was 1.164. This was 1.7% lower than the same average for Configuration 7A. Also included in Figure 15.6 is the distribution on the outer surface of the fuel. The comparison of these points with Configuration 7A has been presented above.

15.2.2 Cadmium Ratios

The cadmium ratios obtained for this assembly are shown in Table 15.2. These are compared to Configuration 7A in Table 15.3. It will be noted that there is no definite trend one way or the other. If it is assumed that there was no change between the two configurations in Regions 1 and 2 and in the axial at the core center, the data show a standard error of 7% which is a little higher than would normally be expected. Region 3 values show a possible increase in cadmium ratio but the increase is just outside the indicated standard error.

TABLE 15.1

Catcher Foil Data - Configuration 7C

Run 1054

Foil No.	Type	Location		Tray No.	Normalized Counts (l)	Ratio of Local to Core Center (Foil No. X)
		Radial (cm)	Axial (cm)			
1	Cd	91.4	212.0	17	4297	.120
2	Cd	91.4	120.6	17	6229	.175
3	Bare	91.4	90.1	17	157(Bad Number)	
4	Cd	61.0	120.6	17	6495	.182
5	Cd	30.5	120.6	17	5091	.143
54	Cd	91.4	90.1	17	5422	.152
6	Bare	0	212.0	17	102880	2.883
7	Bare	0	196.8	17	58944	1.652
8	Bare	0	181.5	17	46141	1.293
9	Bare	0	166.3	17	38142	1.069
10	Bare	0	151.1	17	35675	1.000 (X)
11	Bare	0	135.8	17	30732	.861
12	Bare	0	120.6	17	25091	.703
13	Bare	0	105.3	17	28571	.801
14	Bare	0	90.1	17	63270	1.773
6	Bare	0	212.0	17	102880	2.883
15	Bare	15.2	212.0	17	91063	2.552
21	Bare	30.5	212.0	17	105333	2.952
30	Bare	42.7	212.0	17	123324	3.456
36	Bare	61.0	212.0	17	138639	3.886
42	Bare	76.2	212.0	17	138884	3.893
48	Bare	91.4	212.0	17	136847	3.836
7	Bare	0	196.8	17	58944	1.652
16	Bare	15.2	196.8	17	57643	1.616
22	Bare	30.5	196.8	17	67579	1.894
31	Bare	42.7	196.8	17	104399	2.926
37	Bare	61.0	196.8	17	128398	3.599
43	Bare	76.2	196.8	17	130698	3.663
49	Bare	91.4	196.8	17	138880	3.892
8	Bare	0	181.5	17	46141	1.293
17	Bare	15.2	181.5	17	49302	1.382
23	Bare	30.5	181.5	17	61976	1.737
32	Bare	42.7	181.5	17	102000	2.859
38	Bare	61.0	181.5	17	126326	3.541
44	Bare	76.2	181.5	17	137824	3.863
50	Bare	91.4	181.5	17	137558	3.855
9	Bare	0	166.3	17	38142	1.069
18	Bare	15.2	166.3	17	43999	1.233
24	Bare	30.5	166.3	17	52120	1.461
33	Bare	42.7	166.3	17	92907	2.604

TABLE 15.1
(Continued)Run 1054

Foil No.	Type	Location		Tray No.	Normalized Counts (1)	Ratio of Local To Core Center (Foil No. X)
		Radial (cm)	Axial (cm)			
39	Bare	61.0	166.3	17	119256	3.342
45	Bare	76.2	166.3	17	123802	3.470
51	Bare	91.4	166.3	17	133450	3.740
10	Bare	0	151.1	17	35675	1.000 (X)
19	Bare	15.2	151.1	17	37934	1.063
25	Bare	30.5	151.1	17	46039	1.290
34	Bare	42.7	151.1	17	68197	1.911
40	Bare	61.0	151.1	17	103848	2.911
46	Bare	76.2	151.1	17	127649	3.578
52	Bare	91.4	151.1	17	133605	3.744
12	Bare	0	120.6	17	25091	.703
20	Bare	15.2	120.6	17	27390	.768
26	Bare	30.5	120.6	17	30211	.847
35	Bare	42.7	120.6	17	40873	1.146
41	Bare	61.0	120.6	17	88857	2.490
47	Bare	76.2	120.6	17	125273	3.511
53	Bare	91.4	120.6	17	132108	3.703

Run 1055

1	Cd	42.7	120.6	17	5408
2	Cd	15.2	196.8	17	5299
3	Cd	0	212.0	17	5248
4	Cd	15.2	166.3	17	5051
5	Cd	42.7	196.8	17	5834

Run 1056

1	Cd	0	196.8	17	5401
2	Cd	0	166.3	17	5061
3	Cd	0	120.6	17	4946
4	Cd	0	90.6	17	6137
5	Cd	42.7	166.3	17	5751

(1) Normalized to 100,000 counts on decay corrector.

TABLE 15.2

Catcher Foil Cadmium Ratios - Configuration 7C

Run No.	Location		Tray No.	Normalized Bare Foil Activity	Normalized Cd Foil Activity	Cd Ratio Bare/Cd Activity
	Radial (cm)	Axial (cm)				
1054,1056	0	90.1	17	63270	6137	10.31
1054,1056	0	120.6	17	25091	4946	5.07
1054,1056	0	166.3	17	38142	5061	7.54
1054,1056	0	196.8	17	58944	5401	10.91
1054,1055	0	212.0	17	102880	5248	19.60
1054,1056	0	120.6	17	25091	4946	5.07
1054,1054	30.5	120.6	17	30211	5091	5.93
1054,1055	42.7	120.6	17	40873	5408	7.56
1054,1054	61.0	120.6	17	88857	6495	13.68
1054,1054	91.4	120.6	17	132108	6229	21.21
1054,1056	0	166.3	17	38142	5061	7.54
1054,1055	15.2	166.3	17	43999	5051	8.71
1054,1056	42.7	166.3	17	92907	5751	16.15
1054,1056	0	196.8	17	58944	5401	10.91
1054,1055	15.2	196.8	17	57643	5299	10.88
1054,1055	42.7	196.8	17	104399	5834	17.89
1054,1054	91.4	212.0	17	136847	4297	31.85
1054,1054	91.4	90.1	17	153269 (1)	5422	28.27

(1) This an estimated number based on previous results. The actual bare foil at this location given in Table 15.1 was obviously not right.

TABLE 15.3

Catcher Foil Cadmium Ratio Comparison - Configurations 7A and 7C

Location		Cd Ratios		Ratio
Radial (cm)	Axial (cm)	Config. 7A	Config. 7C	Config. 7C/Config. 7A
0	90.1	11.80	10.31	0.87
0	120.6	4.71	5.07	1.08
0	166.3	8.09	7.54	0.93
0	196.8	9.94	10.91	1.10
0	212.0	18.88	19.60	1.04
0	120.6	4.71	5.07	1.08
30.5	120.6	6.23	5.93	0.95
42.7	120.6	7.26	7.56	1.04
61.0	120.6	17.01	13.68	0.80
91.4	120.6	21.02	21.21	1.01
0	166.3	8.09	7.54	0.93
15.2	166.3	8.07	8.71	1.08
42.7	166.3	16.52	16.15	0.98
0	196.8	9.94	10.91	1.10
15.2	196.8	9.78	10.88	1.11
35.1	196.8	17.66	17.89 (1)	1.01
91.4	212.0	28.36	31.85	1.12
91.4	90.1	26.73	28.27	1.06

(1) On Configuration 7C this point was at a radial distance of 42.7 cm.

Fixed Table

124 Surfaces with 6 Sheets per Surface
 46 Surfaces with 5 Sheets per Surface
 Total - 974 Sheets

Fig. 15.1 Fuel tray installation pattern - configuration 7C - region 3

Fig. 15.2 Radial power distribution from bare catcher foils - configuration 7C

Fig. 15.3 Radial power distribution from back catcher foils - configuration 7C

Fig. 15.4 Radial power distribution from bare catcher foils - configuration 7C

Fig. 15.5 Radial power distribution from bare catcher foils - configuration 7C

Fig. 15.6 Axial power distribution for core, as shown in Figure on 7C

16.0 CONFIGURATION 8

This configuration was the same as 7B except for an increase in fuel loading. The experiment initially required a neutron lifetime measurement with 5% more fuel in the reactor. The increase in reactivity was to be poisoned down with a $1/v$ absorber. After considering the relatively small change in reactivity and the correspondingly small change in neutron lifetime for a 5% increase in fuel, it was decided to increase the loading 20%.

There were no power distribution or foil exposure measurements required or obtained for this assembly.

16.1 Rod Worth and Reactivity Measurements

The base k-excess prior to adding fuel was $0.245 \pm 0.012\% \Delta k$ based on a total rod worth (actuators 1 to 7) of $-5.255 \pm 0.263\% \Delta k$. A 10% increase in fuel on Trays 1 to 8 (131 sheets, 343.7 gm) increased k-excess to $0.575 \pm 0.029\% \Delta k$ for a net increase of $0.330 \pm 0.031\% \Delta k$. The 10% change was then completed for Trays 1 to 16 for a total fuel addition of 375 sheets amounting to 990.2 gm. Excess reactivity measured to be $1.068 \pm 0.053\% \Delta k$. The net increase for a 10% increase in fuel over half of the reactor was $0.823 \pm 0.054\% \Delta k$. The average fuel worth resulting from these measurements would be $(0.831 \pm 0.055) \times 10^{-3} \% \Delta k / \text{gm}$.

The extrapolated increase in k-excess for a 10% increase in fuel in Configuration 7B would be $1.646 \pm 0.109\% \Delta k$. This gives a $\Delta k/k/\Delta m/m$ of 0.17 compared to 0.24 for Configuration 3B.

A total of 1555 sheets, 4077 grams of fuel, was added to the fueled region. Of this total, 1008 sheets, 2 per surface, went to Region 1 and 547 sheets were uniformly dispersed over Region 2. The average weight of the additional fuel was 2.62 ± 0.03 gm per sheet. The fuel distribution is summarized in Table 16.1. The increased multiplication was poisoned down by placing 8 boron carbide filled rods evenly spaced over the fueled region of the cavity as shown in Table 16.2. These rods were 1.27 cm in diameter and 109.5 cm long overall dimensions. The active portion of the rod contained 1.0 gm/cc natural boron over 69.9 cm of the rod length. The cladding was 0.0635 cm thick, 304 stainless steel.

The final k-excess, with the neutron generator in place, was $0.110 \pm 0.005\% \Delta k$ with all rods withdrawn and the D_2O temperature of 21°C . This was the condition of the reactor for the neutron lifetime measurements.

The worth of actuator 7 was measured twice during the course of adding fuel to the reactor. Its worth was $-0.745 \pm 0.017\% \Delta k$. This actuator was the same as actuator 6 except for minor variations in individual rods. Compared to actuator 6 worth on Configuration 3A, the above actuator worth was $3.2 \pm 5.2\%$ higher than actuator 6.

16.2 Neutron Lifetime Measurements

Neutron lifetime measurements with the 20% increase in fuel gave a weighted average lifetime of $(2.56 \pm 0.05) \times 10^{-3}$ sec. The data are given in Table 16.3. This value is 26.4% lower than before the increase in fuel loading.

Neutron lifetime is inversely proportional to Σ_a . Within the fueled region Σ_a changed by about 40% which would result in a 29% (1/1.4) decrease in neutron lifetime within the cavity. Since 15 to 25% of the absorption occurred outside of the cavity region, the overall core lifetime would have changed by something less than 29% which takes into account the fueled region only. The measured change, given above, appears to be consistent with this reasoning.

TABLE 16.1

Critical Fuel Loading Arrangement - Configuration 8

Region 1			
Tray No.	Number of Surfaces	Fuel Sheets per Tray (1)	Fuel Weight (2) (gm)
1	2	24	62.9
2	8	96	251.5
3	10	120	314.4
4	12	144	377.3
5	14	168	440.2
6	14	168	440.2
7	16	192	503.0
8	16	192	503.0
9	18	216	565.9
10	18	216	565.9
11	18	216	565.9
12	20	240	628.8
13	20	240	628.8
14	20	240	628.8
15	20	240	628.8
16	20	240	628.8
17	20	240	628.8
18	20	240	628.8
19	20	240	628.8
20	20	240	628.8
21	20	240	628.8
22	20	240	628.8
23	18	216	565.9
24	18	216	565.9
25	18	216	565.9
26	16	192	503.0
27	16	192	503.0
28	14	168	440.2
29	12	144	377.3
30	12	144	377.3
31	8	96	251.5
32	6	72	188.6
Totals	504	6048	15845.6

(1) Equivalent size 1.0 sheets

(2) Based on 2.62 grams per fuel sheet

TABLE 16.1
(Continued)

Region 2			
Tray No.	Number of Surfaces	Fuel Sheets per Tray (1)	Fuel Weight (2) (gm)
3	4	32	83.8
4	8	64	167.7
5	10	80	209.6
6	12	95	248.9
7	12	96	251.5
8	14	111	290.8
9	16	127	332.7
10	16	129	338.0
11	16	126	330.1
12	16	129	338.0
13	18	145	379.9
14	18	143	374.7
15	18	144	377.3
16	18	143	374.7
17	18	144	377.3
18	18	144	377.3
19	18	143	374.7
20	18	143	374.7
21	18	144	377.3
22	16	129	338.0
23	16	126	330.1
24	16	129	338.0
25	16	128	335.4
26	14	111	290.8
27	12	96	251.5
28	12	96	251.5
29	10	80	209.6
30	8	64	167.7
31	4	32	83.8
Totals	410	3273	8575.4

(1) Equivalent size 1.0 sheets

(2) Based on 2.62 gm per fuel sheet

TABLE 16.2

Boron Carbide Control Rod Locations in Cavity - Configuration 8

Tray Number	Surface Number
9	6
9	14
15	6
15	15
19	11
23	4
23	15
28	9

TABLE 16.3
Neutron Lifetime Measurements - Configuration 8

Run No.	Channel Width (m sec)	Pulse Rate (sec ⁻¹)	Subcritical Level (% Δk)	Bkg. (CPM)	Intercept (CPM)	Alpha (sec ⁻¹)	± Error on Alpha (sec ⁻¹)
8-1	5.12	0.67	5.1	399	1218	-19.14	0.28
8-2	5.12	0.67		381	1231	-18.87	0.28
8-3	1.28	2.0		256	1112	-20.29	0.22
8-4	1.28	2.0		252	1092	-20.82	0.23
8-5	0.32	10.0		356	975	-23.12	0.84
8-6	0.32	10.0		469	820	<u>-23.16</u>	1.11
						-20.09 ± 0.12 (1)	
8-9	5.12	0.67	2.0	494	518	-10.88	0.29
8-15	5.12	0.67		571	448	-10.35	0.30
8-8	1.28	2.0		550	315	-12.87	0.62
8-14	1.28	2.0		652	569	-11.29	0.60
8-7	0.32	10.0		944	477	<u>-15.11</u>	2.25
						-10.98 ± 0.19	
8-10	5.12	0.67	1.0	909	522	- 6.81	0.18
8-11	5.12	0.67		1323	717	- 6.93	0.17
8-12	1.28	2.0		1190	792	- 6.74	0.29
8-13	1.28	2.0		1377	612	<u>- 8.69</u>	0.39
						- 7.03 ± 0.11	

$$\ell = \frac{(.00765 \times 6.67 \times .949) + (.00765 \times .949)}{20.09 \pm 0.12} = 2.78 \pm .13$$

$$\ell = \frac{(.00765 \times 2.61 \times .98) + (.00765 \times .98)}{10.98 \pm 0.19} = 2.48 \pm .06$$

$$\ell = \frac{(.00765 \times 1.31 \times .99) + (.00765 \times .99)}{7.03 \pm 0.11} = 2.50 \pm .07$$

$$\text{Weighted Average} \quad \underline{\underline{2.56 \pm 0.05}}$$

(1) All errors for results at a given subcritical level are assumed to be purely statistical counting uncertainties.

17.0 REACTOR CALCULATIONS OF THE EXPERIMENTAL EFFECTS

The experimental results were not all necessarily as anticipated, but it is expected that an understanding where differences occurred will evolve. Presumably most of the results can be deduced, after the fact, through elementary principles of nuclear reactor theory. Those that are not so obvious can hopefully be explained by multi-energy group calculations, or, vice versa, the deficiencies in the multi-energy group calculations can be deduced from the experiment.

The principal purpose of the work described in this report was experimental. However, some analytical work with computer codes was performed so as to make adequate pre-analysis and preparations for the experiment, as well as to help explain the measured results. These calculations were not of great sophistication. Codes amenable to short (3 to 30 minutes) running times on an IBM 7040 computer were the only ones employed, and only a limited amount of analysis was performed. This section briefly describes the calculations performed and their inherent and discovered limitations and summarizes the correlation efforts and conclusions.

17.1 Cross Section Sets

All the calculations were performed using the 20-level cross section sets of the GE-NMPO library, either in unreduced 19-group format or in few group (4 or 5) reduced format. The energy structure of this cross section set is listed in Table 17.1. The cross sections that have been used for the principal reactor constituents, enriched uranium (Oralloy), aluminum, bound deuterium, oxygen and beryllium are presented in Table 17.2. Modifications have been made to some of these cross sections to simulate the (γ -n) effects in the beryllium and heavy water, and to give improved correlation with experiment for the flux distribution in the heavy water.

17.2 Gamma-Neutron Production Cross Sections

The photoneutron production cross sections probably have a minor effect on the relative worth of beryllium with respect to heavy water since the production of neutrons by gamma rays is substantially higher in beryllium after long irradiation times.⁽⁶⁾ Therefore, a production cross section was added to the upper energy group (7.8 to 10.0) MeV of Be and D₂O to simulate the production of neutrons by gamma rays originating from the core. The neutrons have about the same attenuation coefficient in Be and D₂O as do the average gamma rays originating from the fuel (0.075 cm⁻¹ in D₂O for the neutrons, 0.05 cm⁻¹ for the gamma rays) and thus provides an adequate simulation for neutron production terms.

Sufficient production cross section was inserted for the production in the D₂O of 1/2 percent of the total neutrons produced in the D₂O-reflected system. This amounted to a production cross section of 0.6 cm⁻¹. For the beryllium, a term four times as large was chosen, with respect to the long irradiation times listed in Reference 6. Use of these extra production terms to simulate photoneutrons brought better

correlation between the calculated and measured beryllium reflector worths, though the agreement desired was still not achieved. There was felt to be little justification for increasing the photoneutron production terms beyond these values.

17.3 One-Dimensional Diffusion Theory Codes

The main code employed for most of the calculations was a 19-energy-group diffusion theory code in spherical geometry. Equivalent volumes were selected for the core, while the reflector thickness was taken as the perpendicular thickness instead of equivalent volumes. The usual total transport cross section was used for calculating the diffusion coefficient. The opposite extreme of calculating the diffusion coefficient in the core by using the transport approximation for only the scattering cross section resulted in a negligible ($0.7\%\Delta k$) effect on reactivity compared to the result when the absorption cross section was included in the diffusion coefficient.

Diffusion theory is generally inapplicable in the core, where the absorption cross section predominates. The core absorption is, however, quite small giving rise to diffusion coefficients on the order of 10^3 cm. However, diffusion theory should work well in the moderator regions, and would be expected to do a very adequate job of predicting differences between moderators.

The bias created by performing a spherical calculations on this cylindrical reactor is not severe. This shape factor was calculated using a course-grid, 4-group cylindrical PDQ model⁽¹¹⁾ and an equivalent spherical model. The difference amounts to approximately $1.5\%\Delta k$, or a 3 cm reduction in the radius that gives the same volume for the core. These differences should have an insignificant effect on calculation of small variations in composition while maintaining the same basic reactor dimensions. The results of the shape factor calculation are shown in Figures 17.1 and 17.2.

This 19-group diffusion theory code can only be used to calculate configurations that have no void regions and therefore is strictly limited only to Configuration 1 in which the fuel filled nearly the full cavity. However, as a rough survey of moderator effects, the fuel loading and fuel diameter should be insensitive parameters, and much use of this code was made for these general calculations because of its speed and energy detail.

On Configuration 1, allowing for a 1.5% shape factor, the 19-group diffusion theory calculation underpredicted the fuel loading by approximately 16% (or overpredicted k by 5%). These results, however, are not too inconsistent with the fuel distribution problems discussed in Section 4. There it was concluded from both analysis and experiment that the discrete distributions of fuel differed from a uniform distribution of fuel by nominally 10% in fuel loading or 3% in k .

Initially the continuous slowing down model ($\xi \Sigma_s$) was used for group transfer cross sections and only single group transfer was employed. However, the bulk of the calculations was done after adding to the program a scatter transfer matrix for both hydrogen (impurity in D_2O) and deuterium. Unfortunately, the good correlation that had been obtained with the less correct model suffered when the scatter transfer matrix was added. The multiplication factor was over-predicted by about 5% on both Configuration 1, and on the Byer's experiment (8) of a foil lined cavity (a 10% shape factor was included in these estimates). However, because the scatter transfer matrix more accurately describes the process of neutron slowing down in the moderator, this matrix was retained for most of the calculations, since these were aimed principally at determining moderator effects.

Four group diffusion theory was used for preliminary survey calculations, but, as the experimental results later proved, with less success than the 19-group code.

17.4 Transport Calculations

The only general transport codes available at the National Reactor Testing Station were few-group one dimensional codes in either cylindrical or slab geometry (9). The former was used with few group cross sections spectral averaged with an "average" cavity reactor spectrum from the GE-NMPO 20 level. The Coveyou-Macauley slowing down model, similar to the Grueling-Goertzel method, was employed.

To account for the transverse leakage in these one-dimensional calculations, a DB^2 leakage term was added to the total cross in all groups and regions. The buckling was obtained from the slope of the flux at the boundary,

$$B^2 = \frac{\int \frac{\partial \phi}{\partial r} \cdot n \, dS}{\int \phi \, dV}$$

i.e., from Gauss' Law $\int \text{div } J \, dV = \int J \cdot n \, dS$. The diffusion coefficient for heavy water was used in the DB^2 term.

Despite accounting for the transverse leakage in these one dimensional calculations the critical fuel loading was still underestimated by nominally 20%. Parallel leakage from the reactor was 10%, approximately that observed in the spherical diffusion calculations, and DB^2 leakage was approximately 25% of the total absorptions. Thus, despite what is ostensibly too large a factor for transverse leakage the multiplication factor is still over predicted by computations using both S_0 and S_1 in-group and group-transfer scatterings, in S_4 geometry. Higher angular order was not attempted because of previously indicated adequacy of S_4 detail (7).

Despite the rather large error in critical loading (or multiplication factor) resulting from the use of this one-dimensional transport code, it was still used to calculate those effects which were generally

sensitive to fuel radius, and for which the more reliable spherical geometry diffusion code could not be used.

17.5 Two Dimensional Diffusion Theory

The PDQ code ⁽¹¹⁾, in four energy group detail, was used to calculate those effects which were definitely two dimensional and not at all feasible for one dimensional analyses. These included the effects of table separation, control rod worth in the end reflector, and removal of the end plug. The results were generally satisfactory except for the end plug calculation. However, again the fuel loading was substantially underpredicted, by the order of 10 to 20% (2 to 5% in k).

This relatively large error in absolute reactivity in all the calculations (few group transport, few group diffusion theory and in the multi-group diffusion theory) indicates that the basic 20 level cross section library may be inadequate. The use of the Coveyou-MacCauley slowing-down model in the few group problems may be a basic trouble. The modified age equation does a much better job on hydrogen moderated system and possibly would have been superior for this heavy water system. However, these calculations appeared to be adequate for the purpose of guiding the experimenters in the control of the experiment.

As for the over-all adequacy of the 20-level cross section library, it appears that the D₂O cross sections may be in need of revision, especially to make these appropriate for use with a scatter transfer matrix. However, the transport code calculations were performed twice, first using the NMPO heavy water cross sections and second using D₂O few group cross sections obtained from a revision of GAM ⁽¹⁰⁾. The two results were comparable, though the NMPO cross sections gave a result slightly closer to a k-effective of 1.0. Thus, instead of being suspicious of these non-thermal cross sections obtained from quite different sources, one is lead to believe that the thermal cross sections may be at fault, perhaps caused by the use of only a single thermal group.

This reasoning does not leave the fuel cross sections without suspicion. However, these have recently been revised in the NMPO library to correspond to the most recent Hanford Cross Section Library and have shown good correlation on a number of different types of critical experiments.

TABLE 17.1
NMPO Nuclear Data Tape Energy Structure

Level	Group	Lethargy from 10 MeV	Energy of Level	Upper Energy of Group	Lethargy Width of Group
0	0	0.0	10.0 MeV	10.0 MeV	0.25
1	1	0.5	6.065	7.8	0.5
2	2	1.0	3.679	4.72	0.5
3	3	1.5	2.231	2.86	0.5
4	4	2.0	1.353	1.74	0.5
5	5	2.5	0.821	1.05	0.5
6	6	3.0	0.498	0.639	0.5
7	7	3.5	0.302	0.388	0.5
8	8	4.0	0.183	0.235	1.25
9	9	6.0	24.79 keV	67.3	2.0
10	10	8.0	3.354	9.11	2.0
11	11	10.0	0.454	1.23	2.0
12	12	12.0	61.44 eV	167 eV	2.0
13	13	14.0	8.315	22.6	1.75
14	14	15.5	1.855	3.93	1.25
15	15	16.5	0.683	1.025	1.0
16	16	17.5	0.251	0.414	1.0
17	17	18.5	0.0924	0.152	1.03
18	18	*	*	thermal	---
19		---	*		

* - The energy level at the cutoff to the thermal group corresponds to the average velocity of the Maxwell Boltzman distribution for the temperature of the medium.

TABLE 17.2

20 Level Cross Sections of Principal Reactor Materials

DESIGNATION	FORMULA	CODE	DENSITY			
*RBE(N,2N)	*RBE(N,2N)	-1.512	1.850			
MATERIAL COMPOSITION						
CODE	WEIGHT FRACTION					
-1.502	0.10000E 01					
LEVEL	LETHARGY	SIGMA SCATTER	XI SIGMA SCATTER	SIGMA TRANSPORT	SIGMA ABSORPTION	NU SIGMA FISSION
0	0.	0.20157E-00	0.14963E-00	0.86564E-01	0.74197E-02	0.64304E-01
1	0.5000	0.22507E-00	0.13912E-00	0.12366E-00	0.12366E-01	0.64304E-01
2	1.0000	0.24980E-00	0.13294E-00	0.19168E-00	0.	0.64304E-01
3	1.5000	0.27453E-00	0.43282E-01	0.17313E-00	0.74197E-02	0.
4	2.0000	0.30050E-00	0.43900E-01	0.21023E-00	0.98930E-03	0.
5	2.5000	0.55648E 00	0.11340E-00	0.50949E 00	0.18549E-03	0.
6	3.0000	0.49465E-00	0.10140E-00	0.44766E-00	0.27206E-06	0.
7	3.5000	0.45137E-00	0.93794E-01	0.41551E-00	0.35862E-06	0.
8	4.0000	0.67025E 00	0.13928E-00	0.62032E 00	0.45755E-06	0.
9	6.0000	0.72961E 00	0.15161E-00	0.67525E 00	0.12490E-05	0.
10	8.0000	0.74197E 00	0.15418E-00	0.68670E 00	0.33884E-05	0.
11	10.0000	0.74197E 00	0.15418E-00	0.68670E 00	0.92252E-05	0.
12	12.0000	0.74197E 00	0.15418E-00	0.68670E 00	0.25103E-04	0.
13	14.0000	0.74197E 00	0.15418E-00	0.68670E 00	0.68138E-04	0.
14	15.5000	0.74197E 00	0.15418E-00	0.68670E 00	0.12824E-03	0.
15	16.5000	0.74197E 00	0.15418E-00	0.68670E 00	0.24621E-03	0.
16	17.5000	0.72095E 00	0.14981E-00	0.66724E 00	0.37111E-03	0.
17	18.5000	0.62079E 00	0.12900E-00	0.57454E 00	0.64663E-03	0.
18	19.7951	0.74197E 00	0.15418E-00	0.68670E 00	0.11494E-02	0.
3000	17.6745	0.72382E 00	0.15041E-00	0.66990E 00	0.42837E-03	0.
2500	17.8306	0.72381E 00	0.15041E-00	0.66988E 00	0.46312E-03	0.
2000	18.0157	0.72380E 00	0.15040E-00	0.66987E 00	0.50801E-03	0.
1500	18.2429	0.72378E 00	0.15040E-00	0.66986E 00	0.56909E-03	0.
1000	18.5375	0.72390E 00	0.15043E-00	0.66996E 00	0.65937E-03	0.
500	18.9568	0.72466E 00	0.15058E-00	0.67067E 00	0.81320E-03	0.
68	19.5549	0.72720E 00	0.15111E-00	0.67302E 00	0.10968E-02	0.

DESIGNATION	FORMULA	CODE	Z	A	XI	1-B
DEUTERIUM	D(HVY WATER)	3.100	1.	2.015	0.726	0.666
LEVEL	LETHARGY	SIGMA SCATTER	XI SIGMA SCATTER	SIGMA TRANSPORT	SIGMA ABSORPTION	
0	0.	0.98000E 00	0.71158E 00	0.65288E 00	0.23138E-07	
1	0.5000	0.13900E 01	0.10093E 01	0.92602E 00	0.29670E-07	
2	1.0000	0.19000E 01	0.13796E 01	0.12658E 01	0.38088E-07	
3	1.5000	0.24800E 01	0.18007E 01	0.16522E 01	0.48760E-07	
4	2.0000	0.29200E 01	0.21202E 01	0.19453E 01	0.63020E-07	
5	2.5000	0.32800E 01	0.23816E 01	0.21851E 01	0.80500E-07	
6	3.0000	0.33500E 01	0.24324E 01	0.22318E 01	0.10350E-06	
7	3.5000	0.33500E 01	0.24324E 01	0.22318E 01	0.13294E-06	
8	4.0000	0.33500E 01	0.24324E 01	0.22318E 01	0.17066E-06	
9	6.0000	0.33500E 01	0.24324E 01	0.22318E 01	0.46460E-06	
10	8.0000	0.33500E 01	0.24324E 01	0.22318E 01	0.12604E-05	
11	10.0000	0.33500E 01	0.24324E 01	0.22318E 01	0.34316E-05	
12	12.0000	0.33500E 01	0.24324E 01	0.22318E 01	0.93380E-05	
13	14.0000	0.33500E 01	0.24324E 01	0.22318E 01	0.25346E-04	
14	15.5000	0.33500E 01	0.24324E 01	0.22318E 01	0.47702E-04	
15	16.5000	0.33500E 01	0.24324E 01	0.22318E 01	0.91586E-04	
16	17.5000	0.37000E 01	0.24324E 01	0.24645E 01	0.13805E-03	
17	18.5000	0.42500E 01	0.26866E 01	0.28313E 01	0.24053E-03	
18	19.7951	0.51000E 01	0.37000E 01	0.34000E 01	0.42757E-03	
3000	17.6745	0.37710E 01	0.28250E 01	0.2437CE 01	0.16000E-03	
2500	17.8306	0.38330E 01	0.28610E 01	0.24820E 01	0.17000E-03	
2000	18.0157	0.39130E 01	0.29080E 01	0.25410E 01	0.19000E-03	
1500	18.2429	0.40220E 01	0.29730E 01	0.2619CE 01	0.21000E-03	
1000	18.5375	0.41810E 01	0.30690E 01	0.27330E 01	0.25000E-03	
500	18.9568	0.44470E 01	0.32320E 01	0.2924CE 01	0.30000E-03	
68	19.5549	0.48990E 01	0.35170E 01	0.32410E 01	0.41000E-03	

TABLE 17.2
(Continued)

DESIGNATION	FORMULA	CODE	Z	A	XI	1-B
CF OXYGEN	CF OXYGEN	3.601	8.	16.004	0.121	0.958
LEVEL	LETHARGY	SIGMA SCATTER	XI SIGMA SCATTER	SIGMA TRANSPORT	SIGMA ABSORPTION	
0	0.	0.92651E 00	0.43426E-00	0.70442E 00	0.25054E-00	
1	0.5000	0.12480E 01	0.23928E-00	0.10226E 01	0.16399E-00	
2	1.0000	0.21945E 01	0.23217E-00	0.17080E 01	0.26315E-01	
3	1.5000	0.13575E 01	0.20891E-00	0.12630E 01	0.10000E 07	
4	2.0000	0.27172E 01	0.41697E-00	0.26029E 01	0.10000E-07	
5	2.5000	0.40768E 01	0.62474E 00	0.38266E 01	0.10000E-07	
6	3.0000	0.66931E 01	0.81527E 00	0.51175E 01	0.10000E-07	
7	3.5000	0.37219E 01	0.59109E 00	0.38984E 01	0.10000E-07	
8	4.0000	0.34243E 01	0.41422E-00	0.32828E 01	0.79282E-07	
9	6.0000	0.34771E 01	0.42038E-00	0.33310E 01	0.21067E-06	
10	8.0000	0.37664E 01	0.45535E-00	0.36082E 01	0.57267E-06	
11	10.0000	0.38000E 01	0.45942E-00	0.36404E 01	0.15560E-05	
12	12.0000	0.38000E 01	0.45942E-00	0.36404E 01	0.42295E-05	
13	14.0000	0.38000E 01	0.45942E-00	0.36404E 01	0.10697E-04	
14	15.5000	0.38000E 01	0.45942E-00	0.36404E 01	0.22298E-04	
15	16.5000	0.38000E 01	0.45942E-00	0.36404E 01	0.38907E-04	
16	17.5000	0.37999E 01	0.45941E-00	0.36403E 01	0.64148E-04	
17	18.5000	0.38514E 01	0.46563E-00	0.36896E 01	0.10576E-03	
18	19.7951	0.40343E 01	0.48775E-00	0.38649E 01	0.15503E-03	
3000	17.6745	0.37624E 01	0.45487E-00	0.36044E 01	0.70000E-04	
2500	17.8306	0.37747E 01	0.45636E-00	0.36162E 01	0.70000E-04	
2000	18.0157	0.37931E 01	0.45859E-00	0.36338E 01	0.80000E-04	
1500	18.2429	0.38217E 01	0.46204E-00	0.36612E 01	0.90000E-04	
1000	18.5375	0.38699E 01	0.46787E-00	0.37074E 01	0.11000E-03	
500	18.9568	0.39634E 01	0.47918E-00	0.37969E 01	0.13000E-03	
68	19.5549	0.41624E 01	0.50323E 00	0.39876E 01	0.18000E-03	

DESIGNATION	FORMULA	CODE	Z	A	XI	1-B
CF ALLMINUM	AL CFINE	5.101	13.	26.980	0.073	0.975
LEVEL	LETHARGY	SIGMA SCATTER	XI SIGMA SCATTER	SIGMA TRANSPORT	SIGMA ABSORPTION	
0	0.	0.15498E 01	0.16611E 01	0.10897E 01	0.14261E-00	
1	0.5000	0.20550E 01	0.15337E 01	0.13808E 01	0.56933E-01	
2	1.0000	0.24335E 01	0.10275E 01	0.17948E 01	0.10333E-01	
3	1.5000	0.28664E 01	0.47472E-00	0.17925E 01	0.39555E-02	
4	2.0000	0.31229E 01	0.25212E-00	0.19497E 01	0.39392E-02	
5	2.5000	0.35846E 01	0.19387E-00	0.24666E 01	0.91684E-03	
6	3.0000	0.39120E 01	0.22151E-00	0.29594E 01	0.99564E-03	
7	3.5000	0.36077E 01	0.22151E-00	0.29589E 01	0.15481E-02	
8	4.0000	0.70733E 01	0.49589E-00	0.66240E 01	0.29511E-02	
9	6.0000	0.39403E 01	0.28764E-00	0.38422E 01	0.47303E-02	
10	8.0000	0.14944E 01	0.10909E-00	0.14572E 01	0.35597E-02	
11	10.0000	0.14022E 01	0.10236E-00	0.13673E 01	0.36500E-02	
12	12.0000	0.14030E 01	0.10242E-00	0.13681E 01	0.50604E-02	
13	14.0000	0.14015E 01	0.10231E-00	0.13666E 01	0.12550E-01	
14	15.5000	0.14251E 01	0.10403E-00	0.13896E 01	0.25716E-01	
15	16.5000	0.14507E 01	0.10590E-00	0.14145E 01	0.45155E-01	
16	17.5000	0.14822E 01	0.10820E-00	0.14453E 01	0.75450E-01	
17	18.5000	0.14342E 01	0.10470E-00	0.13985E 01	0.12234E-00	
18	19.7951	0.14096E 01	0.10290E-00	0.13745E 01	0.17882E-00	
3000	17.6745	0.14717E 01	0.10743E-00	0.14351E 01	0.79700E-01	
2500	17.8306	0.14735E 01	0.10757E-00	0.14368E 01	0.86100E-01	
2000	18.0157	0.14758E 01	0.10773E-00	0.14391E 01	0.94500E-01	
1500	18.2429	0.14784E 01	0.10792E-00	0.14416E 01	0.10590E-00	
1000	18.5375	0.14815E 01	0.10815E-00	0.14446E 01	0.12260E-00	
500	18.9568	0.14841E 01	0.10834E-00	0.14471E 01	0.15130E-00	
68	19.5549	0.14753E 01	0.10770E-00	0.14386E 01	0.20400E-00	

TABLE 17.2
(Continued)

DESIGNATION	FORMULA	CODE	DENSITY			
*M1 ORALLOY	*M1 ORALLOY	-1.132	18.700			
MATERIAL COMPOSITION						
CODE	WEIGHT FRACTION					
-1.081	0.10000E-01					
-1.083	0.40000E-02					
-1.085	0.93180E 00					
-1.088	0.54200E-01					
LEVEL	LETHARGY	SIGMA SCATTER	XI SIGMA SCATTER	SIGMA TRANSPORT	SIGMA ABSORPTION	NU SIGMA FISSION
0	0.	0.20425E-00	0.38952E-01	0.76473E-01	0.87091E-01	0.27746E-00
1	0.5000	0.26444E-00	0.10780E-00	0.12082E-00	0.64866E-01	0.18908E-00
2	1.0000	0.30716E-00	0.12228E-00	0.16980E-00	0.58328E-01	0.15741E-00
3	1.5000	0.30419E-00	0.85079E-01	0.17769E-00	0.62676E-01	0.15929E-00
4	2.0000	0.27755E-00	0.57946E-01	0.17732E-00	0.62372E-01	0.14819E-00
5	2.5000	0.26713E-00	0.47952E-01	0.18798E-00	0.61423E-01	0.13665E-00
6	3.0000	0.30587E-00	0.38239E-01	0.22773E-00	0.64928E-01	0.13785E-00
7	3.5000	0.36120E-00	0.27936E-01	0.28538E-00	0.74510E-01	0.15085E-00
8	4.0000	0.44534E-00	0.21744E-01	0.39361E-00	0.99094E-01	0.18962E-00
9	6.0000	0.49403E-00	0.47440E-02	0.48889E-00	0.17583E-00	0.30982E-00
10	8.0000	0.50028E 00	0.42756E-02	0.49881E-00	0.34518E-00	0.58491E 00
11	10.0000	0.66925E 00	0.57167E-02	0.66730E 00	0.96702E 00	0.15565E 01
12	12.0000	0.11166E 01	0.95306E-02	0.11134E 01	0.25383E 01	0.38747E 01
13	14.0000	0.57409E 00	0.49041E-02	0.57244E 00	0.38459E 01	0.41054E 01
14	15.5000	0.52554E 00	0.44948E-02	0.52406E 00	0.16621E 01	0.30195E 01
15	16.5000	0.59407E 00	0.50806E-02	0.59238E 00	0.37069E 01	0.76886E 01
16	17.5000	0.64031E 00	0.54780E-02	0.63848E 00	0.93615E 01	0.18695E 02
17	18.5000	0.66547E 00	0.56919E-02	0.66355E 00	0.14170E 02	0.29196E 02
18	19.7951	0.67536E 00	0.57777E-02	0.67339E 00	0.22660E 02	0.47011E 02
3000	17.6745	0.65359E 00	0.55909E-02	0.65171E 00	0.11900E 02	0.24238E 02
2500	17.8306	0.65636E 00	0.56133E-02	0.65448E 00	0.10236E 02	0.20811E 02
2000	18.0157	0.65634E 00	0.56132E-02	0.65446E 00	0.11394E 02	0.23173E 02
1500	18.2429	0.65628E 00	0.56126E-02	0.65440E 00	0.12898E 02	0.26290E 02
1000	18.5375	0.65614E 00	0.56115E-02	0.65427E 00	0.15055E 02	0.30813E 02
500	18.9568	0.65585E 00	0.56091E-02	0.65398E 00	0.18867E 02	0.38841E 02
68	19.5549	0.65514E 00	0.56032E-02	0.65327E 00	0.26493E 02	0.54749E 02

Fig. 17.1 Cavity reactor-effect of reflector thickness on k_{eff} - one dimensional spherical calculation

Fig. 17.2 Cavity reactor - sphere to cylinder shape factor - volume of $3.2 \times 10^6 \text{ cm}^3$

18.0 ANALYTICAL VS EXPERIMENTAL CORRELATION AND CONCLUSIONS

Much of the experimental results can be adequately correlated by use of two dimensional transport theory, or in certain cases with one dimensional spherical transport theory. Therefore, in addition to attempting to correlate the less sophisticated calculations, discussed in the previous section, the work at several other laboratories is cited for comparison, these are given in References 7 and 9.

18.1 Critical Mass vs Radius

The required critical mass measurements on the cavity reactor with various fuel to cavity radius ratios were compared to similar data from a Los Alamos cavity reactor ⁽⁹⁾, as shown in Figure 18.1. The Los Alamos reactor contained a 50.8 cm D₂O reflector and a 101.60 cm diameter by 101.60 cm long cavity. The Los Alamos data are normalized to a critical loading of 6.6 kg U-235 and the present experiment to 10.0 kg. The Los Alamos reactor, which had a length/diameter of 1.0, showed a much slower change in critical mass as the fuel radius was reduced than did the present experiment until the radius to cavity ratio was less than about 0.65. Below a ratio of about 0.6, the penalty becomes more severe for the smaller system. It appears as if the minimum radius ratio (for a predominantly thermal core) is larger for the Los Alamos geometry than for the present experiment. The calculations performed in Reference 7 on a plutonium core with mixed reflectors indicate minimum thermal core radius ratios considerably smaller, in the range of 0.2. The same is true for the U-233 systems calculated in Reference 1.

18.2 Fractional Fuel Worth

The worth of a fractional portion of fuel, normally expressed as $\Delta k/k/\Delta m/m$, is of primary interest from control considerations for a nuclear rocket. Experimentally the fuel worth, averaged throughout the core, was obtained from measurements made near the core center and those made at the outer periphery of the core. The power profile was used to interpolate between these two radii. The fuel worth is proportional to the flux and adjoint product, but calculations (in spherical geometry) show less than a 3% change in the thermal adjoint flux across the core, and essentially no change in the faster adjoint fluxes. Thus, the fuel worth profile should be the same as the power profile.

Figure 3.3 shows the variation in fuel worth as determined experimentally among the various configurations. Figure 18.2 attempts to display both the effect of fuel loading, at constant radius for a fuel radius of 2/3 the cavity radius, and the effect of beryllium placement at this constant fuel radius and also at a constant fuel loading (18.5 kg). The experimental curve showing the effect of beryllium is largely quantitative, but does show an increase in fractional fuel worth as the beryllium is moved from a position near the cavity wall to approximately the position of maximum reactivity. As the beryllium moves out further, the fuel worth decreases, eventually returning to values obtained with the pure D₂O reflector. The calculated curves give qualitatively the same

effect vs beryllium location The calculations show that all the beryllium cases have greater fuel worth than pure D_2O and this is substantiated by the experimental results as will be observed from the figure.

18.3 Fuel Acentricity

The position of the high temperature gaseous fueled region within the cavity of an actual nuclear rocket may be expected to vary both in size and in radial position. The optimum location of a given volume of fuel would normally be the centered location. This has been verified both in this experiment and in the Los Alamos experiment (9) for constant diameter fuel distributions. The fuel diameter was 0.60 of the cavity radius in the Los Alamos experiment, and 0.67, in this experiment. The results are shown graphically in Figure 18.3.

In the case of the variable density and variable radii fuel loadings, the acentricity effect of the low density small diameter end of the fuel region was positive, somewhat unexpected. Evidently this portion of the fuel is normally at a definite geometric disadvantage, being somewhat shielded by the larger diameter fuel regions adjacent to it. Any motion which tends to expose more of the shielded region to flux longitudinally traversing the void has a significant positive effect. This positive contribution was greater in magnitude, at least for the measured Configuration 7C, than was the natural propensity for the greatest radial interaction rates to occur with the fuel region centered in the cavity. This net positive effect was 2/3 of the magnitude of the negative effect of shifting the uniformly loaded fuel region.

18.4 Beryllium Reflector Sections in the D_2O

The insertion of beryllium into the heavy water to act as a heat shield and/or water flow baffle resulted in selection of the one position of the three that had the lowest penalty in multiplication factor. This was at an average position for the inner wall of the beryllium at 6.55 cm from the wet surfaces of the cavity wall (usually reported at 5.8 cm, the position of the tangent). This result and those from the other two locations measured are shown in Figure 18.4. As will be noted, the existence of a distinct minimum around 6.55 cm appears to be inconclusive as the error bars overlap for 6.55 cm and 11.55 cm (reflecting uncertainty in the penalty with respect to D_2O). Nevertheless, the data from Configurations 5A and 5B (6.55 cm location) when compared directly to Configuration 6 (11.55 cm location) show that the Be at 6.55 cm gave a higher multiplication by as little as 0.3% Δk or as much as 1.0% Δk than at 11.55 cm. The fuel loading for Configuration 5B was 18.5 kg whereas Configuration 5A contained 21.5 kg. This difference may account for the indicated variation in the result if the Be worth varies with fuel loading.

Also shown in Figure 18.4 are the results of various calculations of the beryllium location effect. These calculations were with 19-group spherical geometry, and the difference results were multiplied by the factor 1/1.75, approximately the ratio of beryllium area to total cavity area in the experiment. It is apparent that the calculations with multiple

down scattering terms give the better correlation with experiment. Inclusion of the photoneutron production cross section terms improves the relative correlation of the reactivity at different locations, but is much too inadequate to account for the differences between calculations and experiment at distances of 5 cm and beyond.

The calculations do show a minimum penalty at the location of about (9 ± 1) cm. (The grid on the calculations was in approximately 2 cm increments.) The experimental minimum could not be precisely located, but it is in the neighborhood of the 6.55 cm location. The minimum is apparently shallow for distances beyond the minimum both from experimental and calculated results.

The calculations further show that the thermal flux "prefers" to peak in the heavy water, and experimental results indicated the same. For instance, there was a very sharp flux peak at the inner edge of the Be at 11.55 cm with the Be at that location as shown in Figure 18.5. The flux peak without beryllium is nominally 15 cm from the cavity wall, both experimentally and in the calculations. As beryllium is inserted near the cavity wall and moved outward so that the 15 cm location passes through the beryllium, the flux does not persist long in the beryllium, but is soon forced to the inner Be wall when this wall is at or near the 10.2 cm spacing.

Net reactor leakage becomes smaller as the beryllium is moved outward, from about 12.5%, in the spherical calculations, with Be against the cavity wall to 6% with the Be at 20 cm. The all D_2O case has about the same leakage as with the Be against the cavity wall. The Be absorbs many more neutrons but produces more neutrons than does the heavy water. The extra absorptions, however are nearly twice the extra productions, (mostly from $n, 2n$ reactions), thus accounting for the major penalty of Be with respect to D_2O .

18.5 Beryllium vs Beryllium Oxide

The measured effect of substituting BeO for Be in which the BeO was found to be significantly less reactive, was quite unexpected. The calculated difference was approximately of the same magnitude, but of opposite sign. The major effect in the calculation was one of absorption, in which the beryllium absorbed 4% more neutrons than did the beryllium oxide.

This somewhat unexpected experimental result stimulated a set of measurements on these two materials in an homogeneous moderated reactor. However, in this reactor both had a positive worth and the ratio of BeO to Be worth was 0.896 ± 0.023 . In this latter case, the better worth of Be can be attributed to its better slowing down power. Such an effect was not observed in the calculations of the cavity reactor, where the absorption cross section differences predominated. The two materials were analyzed by emission spectrograph for boron impurities, with the result that the Be had 11 ppm boron (by weight) and the BeO less than 5 ppm. Thus, it appears that the calculations have indicated too great an importance to absorption (perhaps because of too large a cross section) and not enough importance to the differences in slowing down power

(perhaps because of inadequate geometric description in the calculational model).

18.6 Worth of Structural Rocket Chamber Lining

The penalty that must be paid for lining the cavity walls with a high temperature structural material is severe. Most neutrons will pass through the walls many times before being absorbed, usually in the reactor core. The number of crossings increases as the fuel diameter is made smaller, and thus the reactivity penalty would be expected to be larger in the configurations with the smaller cores. Only one fuel radius, $0.67 R_O$, was employed in the cavity liner measurements. The measurement result and the normalized results of both the spherical multigroup diffusion theory calculations and the cylindrical (one dimensional) few group transport calculations are listed in Table 18.1. The agreement is satisfactory for the diffusion calculation but significantly low for the transport calculation. The penalty in fuel loading is severe, --nominally an extra 30 to 40 kg of fuel being required to compensate for 0.254 cm of stainless steel on the entire cavity wall.

The effect of the liner is essentially one of neutron absorption, and other material worths can be scaled by their thermal absorption cross sections with respect to steel. Resonance absorption cross sections would not be expected to have much effect, since the root mean square slowing down distance in the moderator-reflector (D_2O) is less than one foot. Therefore, neutrons make fewer traverses across the cavity during slowing down than during the thermal migration, and minor absorption resonances in intermediate atomic weight metals should be insignificant. Therefore, thicknesses up to the 0.254 cm thickness of stainless steel (or the equivalent attenuation of other medium weight materials) give a reactivity effect that is approximately linear with thickness of the liner.

18.7 Moderator Temperature Coefficient

The temperature coefficient of the moderator was calculated using the 19-group diffusion theory code.* The effects included were:

1. Maxwell-Boltzmann temperature effects on the thermal cross section group.
2. Aluminum expansion, included only as an expansion of the D_2O reflector region.
3. Heavy water expansion obtained from the table in Reference 5.

Of these various effects, the aluminum expansion was the least, contributing only a few percent of the total effect.

* In these calculations, only a single down scattering group was used, but results of temperature coefficient calculations should be relatively insensitive to the number of downscatter groups depending principally on the thermal group(s).

The temperature effect determined from the experiment, from the calculations, and that measured on the Los Alamos Cavity Reactor⁽⁹⁾ are plotted in Figure 18.6. Note that the Los Alamos Reactor had a smaller core and thinner reflector (50.8 cm vs the 88.9 cm in this experiment). It is, therefore, to be expected that its temperature coefficient would be much larger because its reactivity is a stronger function of moderator density.

The calculations overestimate the temperature coefficient by approximately 50% over the 38°C range of the measurements. There could be a number of reasons for the discrepancy. The use of only a single thermal group is a significant analytical reason. Likewise differential expansion between the cavity and the fuel region were not considered. Experimentally, a number of difficult-to-evaluate factors might be involved, such as change in rod worth caused by differential positioning of the actuators with respect to the moderator as the temperature is varied. Small changes in the table separation gap might have occurred. But such experimental differences are estimated to be much smaller than the correlation discrepancy involved.

18.8 Spectral Indices (Cadmium Ratios) in Reflector

The spectrum in the reflector of the cavity reactor is a very close approximation to a $1/E$ spectrum in the slowing down region. For instance, the measured gold and indium cadmium ratios (total activity divided by epi-cadmium activity) indicated identical values for flux per unit lethargy in their respective resonance regions. Calculations indicate the same constant flux per unit lethargy, a $1/E$ spectrum, throughout the reflector.

The amount of thermal flux relative to slowing down flux, however, varies throughout the reflector and can most conveniently be measured with cadmium ratios. A high value for the ratio indicates a large thermal (sub-cadmium) flux component with respect to the slowing down flux. Figure 18.7 shows the variation in gold cadmium ratio throughout the first two feet of reflector. The experimental results give a lower cadmium ratio than any of the multigroup diffusion calculations. At a distance of two feet from the cavity wall (2/3 of the way to the edge of the reflector), the calculated cadmium ratio is nominally twice the measured ratio.

The calculated results can be varied somewhat by the type of model used. Increasing the fuel mass decreases the cadmium ratio. Furthermore, the scatter transfer matrix gives a larger ratio than is obtained by using only a single down-scattering group. None of these variations are sufficient to bring the calculated results into agreement with the experiment.

This lack of correlation between experiment and analysis is consistent with the previously cited difficulties. The calculated thermal flux is too large compared to the slowing down flux. The excess thermal flux is either being produced too fast, via moderation, or not being absorbed or lost by leakage rapidly enough. If the losses at thermal energies were increased, both the cadmium ratio and the multiplication

factor would be decreased, creating better correlation with the experiment.

The 10.16 cm beryllium baffle in the reflector had little effect on the cadmium ratio traverse across the reflector. A slight reduction (15%) in the cadmium ratio occurs in the region of the beryllium, as observed in the calculations. Essentially no change was observed in the experiment.

18.9 Neutron Lifetime

The prompt neutron lifetime was determined from measurements of the prompt decay of a pulsed neutron source. The subcritical condition of the system was evaluated by the usual method using control rod positions and shape curves. The neutron detector was located outside the D₂O reflector and the time decay was analyzed for the prompt fundamental mode by eliminating the initial portions of the trace which included contributions from higher modes. The neutron lifetime was calculated using the $1/v$ -poisoning method. In this well known method, a dilute concentration of $1/v$ absorber (no other cross sections) is added throughout the reactor system. The neutron lifetime is then determined from the reactivity change of the direct multigroup flux calculation as

$$\beta = \frac{\Delta k}{v \Sigma_a}$$

where $v\Sigma_a$, the product of macroscopic absorption cross section and velocity is a constant, independent of neutron energy. To assure that the conditions of first order perturbation theory were met, the calculations were made at several different concentrations and the calculated lifetime extrapolated to infinite dilution for the $1/v$ -absorber. All calculations were performed on the nominally delayed-critical reactor system. Table 18.2 summarizes the correlation of calculations with experimental results.

The calculated neutron lifetime is consistently lower than the measured, by 15 to 35% with diffusion theory to nearly 50% with transport theory. The fact that the calculated results are low is not surprising, for the calculated multiplication factor was the order of 10% too large. This difference is caused in part by the spherical geometry bias for the diffusion calculations, but there still exists as yet an unresolved 3 to 6% error in multiplication factor. If the fuel loading were reduced sufficiently (15 to 30%) to eliminate this latter bias, then the corresponding reduction in absorptions in the core and increase of absorptions in the reflector would create close agreement between the diffusion theory results and the experiment. The severe bias on the transport theory result is not understood.

The calculations show a decrease in lifetime as the fuel loading is increased, about the same ratio as was observed experimentally between Configurations 7B and 8. The calculations also indicate a reduction in neutron lifetime when beryllium is added to the reflector,

an effect to be expected because of the increased absorption in the beryllium. The experimental results however, show an increase in lifetime of Configuration 7B with respect to Configuration 3B. Both the fuel loading was increased and beryllium was added in this transition. The average fuel diameter was also decreased by 5%, resulting in a 4% increase in the void region, and the fuel was altered longitudinally. Both of these changes would probably create an increase in the lifetime because more crossings of the cavity would be made by the average neutron. This latter effect is evidently responsible for the major difference between the lifetime in Configurations 7B and 3B.

The influence of the neutron lifetime on control aspects of a nuclear rocket reactor is not too much different from the effects of delayed neutrons. The decay constants of the two (of six) shortest lived U-235 precursors (3.0 and 1.1 sec^{-1}) are the same order of magnitude as the prompt neutron decay constant at delayed critical (about 2.3 sec^{-1}). This decay constant will increase with an increase in fuel loading or an increase in the fuel radius. Thus, the condition of the cavity fuel volume is a significant factor in the low frequency (0.1 to 1.0 cycle/sec) behavior of the reactor transfer function gain as shown in Figure 18.8. There is no plateau separating the delayed neutron effects from the prompt lifetime, and the gain essentially drops off steadily at 20 db per decade . There is a nearly constant 1 to 1.5 db difference between the gain of each of the three configurations measured, corresponding to a 3 to 6% variation in the amplitude of the transfer function.

18.10 Hydrogen in Cavity Void

A concentration of 2×10^{21} atoms/cc of hydrogen in the void region gives a total of 6000 atomic moles of hydrogen in the cavity. The final reported value for the worth (Section 11.1) was $-11.6\% \Delta k$. This was obtained from a linear extrapolation of the measured worth over a 22° sector of hydrogen in the form of polyethylene distributed radially throughout the void sector.

Referring to Section 11.1, the original measurement with polyethylene lumped near fuel, verified with a repeat measurement, gave a worth about $2\text{-}1/2$ times the above value. When water was substituted for polyethylene and placed near the cavity wall the hydrogen was worth about 40% of the above value. These two materials were checked for equivalent (suspecting that the CH_2 contained boron) in a critical experiment nuclearly equivalent to the MTR, but somewhat overmoderated. Both substances had a negative worth almost in the ratio identical to their hydrogen atom content. It was thus clear that the position of the hydrogen in the void of the cavity had a strong influence on its worth. The distributed measurements approximately averaged the previous two results.

The cause of the strong position dependence of hydrogen worth in these measurements is the reflecting properties of the CH_2 and H_2O molecules for neutrons trying to reach the core from the reflector. At energies above the molecular binding energy, the scattering is predominately forward resulting in good transmission, but at thermal energies the nearly isotropic scattering creates a reflector barrier. In the case

of a nuclear rocket, there would be little or no molecular binding of the hydrogen molecule which is much lighter than the CH_4 and H_2O molecules, and the reflection effect would not be as severe. The thermal flux reflection effect at room temperatures with the critical experiment is shown in Figure 18.9, as calculated with transport theory using first moment scattering. Typical data obtained with flux profiles from the critical experiment measurements on Configuration 5 are shown for comparison.

The calculated worth of 2×10^{21} atoms/cc (6000 moles) of hydrogen in the void region gave $-11.1\% \Delta k/k$ from transport theory where as the measured value was $-11.6 \pm 0.4\% \Delta k/k$. In this instance, one dimensional cylindrical transport theory gave excellent correlation.

18.11 Two Dimensional Effects

Two dimensional calculations were made using the PDQ(11) computer code to determine control rod worth, table separation effects on reactivity and end plug worth. A single control rod placed in the center of the end reflector gave a total calculated worth of $-0.22\% \Delta k$. All of the actuators near the radial center of the end reflector contained three control rods. A group of three rods were measured to be worth approximately $-1.0\% \Delta k$ which would give a single rod worth of $0.33\% \Delta k$. The three rod cluster would cause significant shadowing on each individual rod, thus the calculation underpredicted rod worth by at least 50% and possibly as much as 100%.

The worth of removing the 12-inch diameter end plug was measured to be $-0.698\% \Delta k$. The PDQ calculation, which simulated the plug with air and used the normal transport approximation for an extrapolation to zero flux, showed a loss due to removing this plug of an extremely large value of $13\% \Delta k$. This gross difference was attributed to the inappropriate combination of the diffusion code, the simulation of the void with very dilute regions, and the huge extrapolation length calculated by the code, resulting in a leakage effect that was much too large.

Table separation calculations were made over several table separation distances. Somewhat the same problem was encountered as with the center plug calculation. But by mixing the aluminum and air for small table separations, extremely dilute regions were avoided and reasonable results were obtained. Table 18.3 shows the comparison between calculations and measured values.

18.12 Concluding Remarks

During the course of this experiment, the test program was planned to obtain the data of most significant interest to the cavity rocket reactor concept and to determine areas which greatly affected the critical mass. Unexpected or questionable results were repeated when such repeat measurements were feasible--i.e., if the configuration had not been altered and an undue amount of set up time required. Therefore, a number of unanswered questions still exist. Some of these are unanswered because of the inadequacy of the calculations, others because certain measurements that were suggested during the course of the experiment could not be scheduled into the program. The obvious or relatively certain conclusions were discussed in the preceding parts of Section 18.

Of particular interest to the cavity rocket reactor concept is the sum total of the effects of reduced fuel radius, hydrogen gas absorption, structural and thermal liner for the cavity, and stability of the system to fuel loading variations. Some of the measurements were made as small perturbations by making a change in one segment of the system. A few of the measurements, particularly hydrogen worth and cavity liner worth would require extrapolations of the order of a factor of 10. Not only is the error of the experimental result multiplied ten fold, but the desirable linear aspects of first order perturbation theory are no longer valid. Furthermore, interpretation of results in terms of reactivity is of little practical interest to the overall concept of a rocket reactor, for what is of primary importance is the fuel loading. This result must be obtained from extrapolations of fuel worth determined with a critical configuration, the fuel loading of which often differed substantially from that of the full engineering mockup. Therefore, the use of the small perturbations is merely sufficient to indicate relative levels of change with respect to a clean critical cavity reactor and to use as guides to show which areas might require further experimentation as full mockups.

Among the many specific experimental effects that remain little understood are the following:

1. Why are thin beryllium oxide slabs within the thick D_2O reflector experimentally a poorer reflector material from a neutronic standpoint than thin beryllium slabs in the D_2O ?
2. What is the effect on neutron lifetime as the fuel radius is changed, while maintaining a critical fuel loading?
3. What happens to the critical loading at smaller radii than the nominal $1/2$ of the cavity radius that was measured?

Some of the experimental results contained unexpectedly desirable implications. For instance, the worth of the exit hole was quite small, and the worth of off-center shifting of the fuel was not as severe as anticipated. Only the cavity liner and hydrogen gas worth contained undesirable implications, and these were deduced only by making large extrapolations to the total effect over the entire reactor.

Thus the discrepancies between theory and experiment while poorly understood analytically, and sometimes disappointing to the designer by no means rule out the feasibility of a practical cavity reactor concept. On the contrary, they point out the ways by which the difficulties might be resolved by more realistic mockups of certain features and alternate approaches to others.

TABLE 18.1

Effects of Fuel Cavity Liner on System Reactivity

	Worth $\% \Delta k/k$
Measured 0.097 cm stainless steel (fuel radius = $0.67 R_o$) *	-15.1
Measured 0.193 cm stainless steel (fuel radius = $0.67 R_o$)	-28.7
Calculated (19-group diffusion theory) 0.193 cm stainless steel (fuel radius = $1.0 R_o$)	-24.5
Calculated (5-group transport theory) 0.193 cm stainless steel (fuel radius = $0.67 R_o$)	-19.3

* R_o = cavity radius

TABLE 18.2

Prompt Neutron Lifetime

Result	Configuration & Fuel Loading	Neutron Lifetime (millisec)
Experiment	3B (No Be) - 15 kg	3.10 ± 0.05
Diffusion Theory	No Be - 10.3 kg	2.6
Transport Theory	No Be - 13.4 kg	2.3
Experiment	7B(Be at 6.55 cm) - 20.3 kg	3.48 ± 0.06
Diffusion Theory	Be at 5.8 cm - 10.3 kg	2.2
Transport Theory	Be at 5.8 cm - 15 kg	1.8
Experiment	8 (Be at 6.55 cm) - 29 kg equiv.	2.56 ± 0.05

TABLE 18.3

Table Separation Reactivity Effects

	Separation Distance	Reactivity Change $\% \Delta k$
Calculated	0.64 cm (mixed Al and air)	-0.8
Measured	0.95 cm (air only)	-0.52
Calculated	2.0 cm (mixed Al and air)	-2.45
Measured	3.49 cm (0.95 cm air and 2.54 cm Al)	-2.27

Fig. 18.1 Comparison of NMPO and Los Alamos cavity reactors on basis of critical mass and ratios of fuel to cavity radius

Fig. 18.2 Effects of beryllium on fuel worth

Fig. 18.3 Effects of off-center shift of fuel

Fig. 18.4 Comparison of calculated vs measured effects of beryllium location in D₂O for fuel loading of 18.5 kg

Fig. 18.5 Relative gold foil activity vs. Be position in reflector

Fig. 18.6 Comparison of temperature coefficients

Fig. 18.7 Gold cadmium ratios in the all D_2O reflected configuration

Fig. 18.8 Zero power transfer function

Fig. 18.9 Thermal flux distribution effects with hydrogen in cavity

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INDEX

Acentricity of fuel, 33, 55, 325-336, 353, 364

Aluminum

in reactor (mass) 21, 41, 42

worth in core, 44

worth in reflector, 162, 163

Axial reference point, 29, 34

Beryllium - partial reflector, 44, 225-291, 353, 365

Beryllium oxide - partial reflector 251, 354

Cadmium ratios (see specific configuration), 34, 36, 47, 356, 368

end-plug effect, 36

beryllium effect, 36

Control system

control rods, 22, 30

worth (see also particular configurations), 22

critical rod positions, 40

rod shape curve, 75-78, 94

Critical loading, 39, 50, 352

bias, 31

Cross sections, 342-345

group structure, 346

Delayed neutrons

β -effective, 23

fraction, 24

Deuterium (see heavy water)

End plug - worth, 162

power distribution effects, 185

Exhaust nozzle, 36, 219

Fission power (see also specific configurations), 23, 33, 68, 106-107, 140

228

specific power, 68, 106-107-140

Flux, 46, 57

Fuel

arrangement, 27, 72, 90, 91, 123, 124, 126

composition, 22, 37

critical loadings, 39, 50, 352

INDEX
(Continued)

Fuel (Cont'd)

- cross sections, 347
- distribution effects, 59, 62, 64, 93
- form, 22
- gap through fuel region, 105, 129
- radius effects, 51, 362,
- reactivity coefficients, 43, 51, 352, 363

Gamma-neutron production, 23, 24, 342

Gamma counting, 24

Gap - (see reactivity, gap between tables)

Generation time (see lifetime)

Hydrogen - coolant worth, 252
flux distribution effects, 359, 370
calculations of worth, 358

Heavy water

- purity, 22
- cross sections (bound deuterium), 347
- expansion, 165

Injector tube, 36, 47, 193

Kinetics

- delayed neutrons, 23, 24
- transfer function, 358, 369

Lifetime (prompt neutron), 37, 167, 168, 180, 310, 317, 338, 341, 357,
361

Neutron lifetime (see lifetime)

Off-center fuel (see acentricity)

Poisoned loading, 337
neutron lifetime change, 338, 341

Reactivity

- gap between tables, 31, 65, 80, 359, 361
- fuel, 43, 51
- various materials (see also specific configurations), 44

Reactivity correction, 31

INDEX
(Continued)

- Reactor power, 33
 distribution (see also specific configurations) , 23 33, 45, 52, 53,
 54, 55, 56
- References, 371
- Reference point (axial), 29, 34
- Reflector
 dimensions, 29
 thickness effect, 350
 beryllium, 44, 225-341, 353, 365
 beryllium oxide, 251, 354
- Resonance integrals (corrections), 69-71
- Shape factor - sphere/cylinder, 343, 351
- Structural lining material, 163, 355, 361
- Temperature coefficient, 33, 164, 172, 181, 250, 355, 367
 calculations, 355, 367
- Variable fuel (core) loading, 33, 34, 54-56, 292-341

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