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Analysis of ZPPR-5 Source Level Flux Monitor Experiments

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ANALYSIS OF ZPPR-5 SOURCE LEVEL FLUX MONITOR EXPERIMENTS

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ABSTRACT

Analysis of 24 configurations of the ZPPR-5 Source Level Flux Monitor experiment has been performed with Modified Source Multiplication Techniques. Transport methods were used to calculate detection efficiencies for the Modified Source Multiplication equation. Detection efficiency changes as large as 40% were observed when going from near critical to approximately −34 ($). Count rate ratios were calculated within 20% of the experimental values. Calculated-to-experimental reactivity ratios near 1.0 were calculated for both a U^{235} fission counter and a BF_3 detector.

A. INTRODUCTION

In 1974 ORNL was requested by ERDA to participate in the analysis of the Source Level Flux Monitoring scheme for the Clinch River Breeder Reactor Plant (CRBRP) largely because of ORNL's involvement in similar work for the Fast Flux Test Facility (FFTF).

Early in the design of CRBRP it was decided to avoid penetrations into the reactor vessel for placement of detection equipment as was done for the FFTF. Thus, the source range monitors used during refueling and startup were placed in graphite blocks outside the reactor guard vessel in the reactor cavity. It was felt that no special cooling would be necessary at this location. Feasibility would be confirmed if sufficient neutron fluence was available and if the background (extraneous sources) count was reduced to levels on the order of 10%. In addition the gamma-ray background must be reduced (using shielding) to levels commensurate with detector technical specifications.

Preliminary analysis performed at ORNL and Westinghouse Advanced Reactor Division (W-ARD) indicated that the neutron fluence background from the stored fuel was too high and thus design changes were made on CRBRP to eliminate the majority (all but four) of stored fuel locations inside the vessel. In addition, experiments were performed at the Tower Shielding Facility (TSF) to determine the effectiveness of the graphite blocks, various counter efficiencies as well as bias factors for determining absolute countrate. Finally, a preliminary analysis indicated that the detector efficiency would not be affected by changes in the control rod positions, but the detector did respond to spatial changes in the inherent source.

Since the Source Level Flux Monitors (SLFM)* are the only plant instrumentation available for detection of reloading or initial loading

*Previously identified as Low Level Flux Monitors.

errors during shutdown, it was felt that a confirmatory critical experiment was needed. Such an experiment was performed for the FFTF low level flux monitoring system and revealed several interesting (fortunately solvable) problems in the design, especially for initial loading.

It was decided by ERDA to divide the experiment into two phases. The initial phase would be performed on the Zero Power Plutonium Reactor (ZPPR) Assembly 5 and would be non-prototypic, but would hopefully address several problem areas. A second (hopefully prototypic phase) would be performed on the expanded ZPPR matrix in the late 1970's and would be used for confirmatory data for the Final Safety Analysis Report (FSAR).

In order to make the first phase more prototypic, ORNL devised a spectral modifier to be used on the ZPPR.[1] Unfortunately, due to lack of available material the recommended special modifier was not used but a similar less effective modifier (polyethylene) was used in its place.[2]

This report summarizes the analyses performed by ORNL on the SLFM phase of the ZPPR Assembly 5 experiment. The findings of these analyses are not prototypic of the CRBRP but the information learned can be used to better understand detector responses of the CRBR ex-vessel detectors and thus will provide additional understanding which will aid in the design of the prototypic CRBR SLFM experiment.

The ZPPR-5 SLFM experiment consisted of detector countrate measurements at 86 configurations and a U^{235} foil experiment.[3] The ORNL analysis utilized the best available transport methods to calculate all steps of the experiment which use polyethylene in the SLFM zone and selected steps where graphite is used in the SLFM zone.

It should be noted that all detection efficiencies calculated in this report are reported on a per gram basis.

B. MODIFIED SOURCE MULTIPLICATION (MSM) TECHNIQUES

The basic MSM equation is:[4]

$$\$_i = \$_o \frac{S_i}{S_o} \frac{W_i}{W_o} \frac{\bar{\nu}_o}{\bar{\nu}_i} \frac{CR_o}{CR_i} \frac{\beta_o}{\beta_i}$$

where:

$S \equiv$ the effective source,

$W \equiv$ the detection efficiency,

$\bar{\nu} \equiv$ the average number of neutrons per fission,

$CR \equiv$ the detector count rate,

$\beta \equiv$ the effective delayed neutron fraction,

and the subscripts o and i refer to reference state o and configuration i respectively. Of the above parameters the detector count rate is obtained experimentally and S, $\bar{\nu}$, and β are integral quantities which can be obtained with little difficulty. The parameter which is not easy to calculate is the quantity (W) called the detection efficiency. This represents the number of reactions in the detector per fission reaction in the core. The equation defining the detection efficiency is:[4]

$$W = \frac{\int_{V_D} \int_E N_o(\bar{r})\, \sigma_r(E)\, \phi(\bar{r},E)\, d\bar{r}dE}{\int_{V_C} \int_E \Sigma_f(\bar{r},E)\, \phi(\bar{r},E)\, d\bar{r}dE} ,$$

where:

$N_o \equiv$ number density of reaction rate material in the detector,

$\sigma_r \equiv$ reaction microscopic cross section in the detector,

$\Sigma_f \equiv$ macroscopic fission cross section,

$V_D \equiv$ volume of detector,

$V_C \equiv$ volume of core, and

$\phi \equiv$ neutron flux.

If the ratio (W_i/W_o) can be calculated accurately, the level of subcriticality can easily be obtained provided a method of calibration is available. The difficulty involved in this calculation is the accurate determination of the neutron flux at the detector location for the various subcritical conditions which may introduce complex flux distributions.

C. AXIAL LEAKAGE CORRECTION

Several three-dimensional calculations were made for the ZPPR-5 project using the Monte Carlo code, KENO.[5] KENO was primarily used to calculate the energy and zone dependent axial leakages. These leakages were then used to form fictitious "cross sections". These fictitious cross sections were determined using the equation:

$$\Sigma_{g,i} = \frac{L_{g,i}}{\phi_{g,i}}$$

where $\Sigma_{g,i}$ is the fictitious cross section for group g and region i, $L_{g,i}$ is the net axial leakage for group g between the region i and the axial blanket, and $\phi_{g,i}$ is the group g volumetric flux associated with region i. These fictitious cross sections were then used in the two-dimensional x-y calculations to account for axial leakage.

D. MODIFIED SOURCE MULTIPLICATION (MSM) CALCULATIONS FOR ZPPR-5 EXPERIMENT

Using the computer code DOT3N5[6] S_4P_3, 44 energy group, transport calculations were made to calculate the neutron flux. Heterogeneity effects in the core were accounted for by cell weighting the core cross sections. The 44 energy group cross sections were collapsed partially from a 126

group structure[7] and partially from a 119 group structure[8] using zone weighting. The resulting reaction rates at all detector locations were calculated using GOFRR.[9] These results were then utilized to determine the detection efficiency to be used in the MSM equation. At each step of the analysis the reactivity inferred by each detector was found and compared to a reference reactivity. The remainder of this report will summarize the results obtained from these calculations.

E. U^{235} FOIL EXPERIMENT

Using U^{235} foils, U^{235} reaction rates were determined at selected points in the reference ZPPR-5 configuration. Figure 1 is a drawing of the reference configuration. The foils were placed on a diagonal from the core center to the source level flux monitor location.

DOT3N5 and GOFRR were used to calculate the U^{235} reaction rates along the diagonal. Reaction rates at the midpoint of each drawer were found and a linear interpolation was used to determine the reaction rate at the actual foil locations. The results for both the experimental and calculated reaction rates were normalized to the value at core center. A comparison of the experimental and calculated reaction rates can be seen in Table 1.

As seen from Table 1 there is only one region where significant differences (on the order to 10 to 15%) are observed. This region is the steel-graphite interface. This overprediction of the reaction rate is apparently a low energy flux perturbation associated with either the cross section structure or the large gradients associated with this boundary. In either case, when compared to other similar calculations, agreement between experimental and calculational results appeared to be extremely good. It should be noted that the starred numbers in Table 1 reflect changes from a previous report.[10]

Table 1. Comparison of Experimental and Calculated U^{235} Foil Reaction Rates

Location	Experimental Reaction Rates	Calculationed Reaction Rates	% Error	
140-34	1.0	1.0	0.0	
142-32	0.8849	0.9012	1.81	Inner Core
144-30	0.7247	0.7481*	3.23*	
146-28	0.5629	0.5801*	3.06*	
148-26	0.4472	0.4529*	1.27*	Outer Core
149-25	0.3577	0.3700*	3.44*	Radial Blanket
150-24	0.2768	0.2847	2.85	
151-23	0.2116	0.2075	- 1.94	
152-22	0.1733	0.1780	2.71	
153-21	0.1860	0.1805	- 2.96	Steel
154-20	0.1623	0.1571	- 3.20	
155-19	0.1163	0.1155	- .69	
156-18	0.0758	0.0792	4.49	
157-17	0.0464	0.0473	1.94	
158-16	0.0310	0.0352	13.54	
159-15	0.0336	0.0382	13.69	Graphite
160-14	0.0246	0.0254	3.25	
161-13	0.0103	0.0097	- 5.83	

*Changes from a previous report.

F. STORED FUEL EXPERIMENT

The stored fuel experiment consisted of two steps (configurations 1 and 2). These configurations are described in Table 2. The reactivity of reference configuration 1 was taken from the Argonne ZPPR-6 Monthly Report for April 1976[11] to be -1.0015 ($). The detectors used for this experiment are described in Table 3. The detection efficiencies found for the various detectors are given in Table 4. These values will be used as reference detection efficiencies in all cases where graphite is used in the SLFM zone.

In configuration 2 a stored fuel assembly is inserted between the SLFM and the core. A summary of the calculations performed with this configuration is found in Table 5. Since no experimental reactivity is given for this configuration, a best estimate of the reactivity must be assumed for comparison purposes. Since detector No. 29 is actually a sum of many in-core detectors, this detector should give a more global representation of the reactivity. Hence it will be assumed that the reactivity inferred by detector No. 29 is the best estimate of the reactivity.

From Table 5 it is clear that when fuel is stored between the SLFM detector and the core, the reactivity can be inferred by the SLFM detector if the detection efficiency correction is known. However as noted the SLFM detection efficiency changes by 10 to 12%. Hence if no detection efficiency corrections are made, a 10 to 12% error will be seen in the reactivity inferred by the SLFM detector. It should be noted that source effectiveness corrections have been considered and found to be negligible since the relative importance of a source at the stored fuel location is very small.

Table 2. Measurement Configurations in the Near-Critical State

Experimental Element	Configuration Description							
	1	2	23	24	25	26	27	28
Main SFS	out	in	out	out	out	out	out	out
Additional SFS	out	out	out	out	out	out	out	out
^{252}Cf Source	out	out	out	out	out	out	137-33	137-28
Zone C	SS	SS	SS	SS	SS	SS	SS	SS
SLFM Zone	Graphite	Graphite	Polyeth	Polyeth	Polyeth	Polyeth	Polyeth	Polyeth
CR01	24.001	24.001	0.0	0.0	0.0	0.0	24.002	24.002
CR02	24.113	24.113	0.222	0.222	0.222	0.222	24.120	24.120
SS01	30.162	30.158	0.075	30.159	0.074	0.074	30.156	30.156
SS04	30.151	30.150	30.155	30.155	30.155	30.155	30.155	30.155
SS05	30.162	30.162	30.175	30.175	30.175	30.175	30.175	30.175
PSR-5, PSR-12	out	out	in	out	out	out	out	out
SS02	out	out	out	in	out	out	out	out
SS03, SS06	out	out	out	out	in	out	out	out
CRP-4	CRP	CRP	CRP	CRP	CRP	CRP	CRP	CRP
CRP-7	CRP	CRP	CRP	CRP	CRP	CRP	CRP	CRP

	29	30	31	32	33	34	35	36
Main SFS	out	out	out	out	out	out	out	out
Additional SFS	out	out	out	out	out	out	out	out
^{252}Cf Source	137-26	137-23	137-21	137-19	137-15	out	out	out
Zone C	SS	SS	SS	SS	SS	SS	SS	SS
SLFM Zone	Polyeth	Polyeth	Polyeth	Polyeth	Polyeth	Polyeth	Polyeth	Polyeth
CR01	24.002	24.002	24.002	24.002	24.002	0.0	0.0	0.0
CR02	24.120	24.120	24.120	24.120	24.120	0.223	0.223	0.223
SS01	30.156	30.156	30.156	30.156	30.156	0.074	0.074	30.156
SS04	30.155	30.155	30.155	30.155	30.155	0.100	0.035	0.035
SS05	30.175	30.175	30.175	30.175	30.175	0.043	0.048	0.048
PSR-5, PSR-12	out	out	out	out	out	out	in	out
SS02	out	out	out	out	out	out	out	in
SS03, SS06	out	out	out	out	out	out	out	out
CRP-4	CRP	CRP	CRP	CRP	CRP	CR	CR	CR
CRP-7	CRP	CRP	CRP	CRP	CRP	CR	CR	CR

	37	38	39	40	41	42	43	44
Main SFS	out	out	out	out	out	out	out	out
Additional SFS	out	out	out	out	out	out	out	out
^{252}Cf Source	out	137-33	137-28	137-26	137-23	137-21	137-19	137-15
Zone C	SS	SS	SS	SS	SS	SS	SS	SS
SLEM Zone	Polyeth	Polyeth	Polyeth	Polyeth	Polyeth	Polyeth	Polyeth	Polyeth
CR01	0.0	0.0	0.0	0.0	0.0	-0.016	-0.016	-0.016
CR02	0.223	0.223	0.223	0.223	0.223	0.223	0.223	0.224
SS01	0.075	0.077	0.077	0.077	0.077	0.077	0.077	0.076
SS04	0.035	0.039	0.039	0.039	0.039	0.039	0.039	0.043
SS05	0.048	0.047	0.047	0.047	0.047	0.047	0.047	0.048
PSR-5, PSR-12	out	out	out	out	out	out	out	out
SS02	out	out	out	out	out	out	out	out
SS03, SS06	in	out	out	out	out	out	out	out
CRP-4	CR	CR	CR	CR	CR	CR	CR	CR
CRP-7	CR	CR	CR	CR	CR	CR	CR	CR

Table 3. Description of Detectors Used in SLFM Experiment

Detector No.	Description
2	Pico No. 1. Located on top of the ZPPR matrix in a polyethylene box, slightly to right of center when facing half 1. Linear BF_3 ionization chamber operated in current mode.
3	Pico No. 2. Same as Pico No. 1.
4	BF_3 proportional counter located on wall of reactor cell directly behind the center of half 2.
5	^{10}B-lined proportional counter located in the plenum behind the center of the half 1 matrix. Reuter-Stokes model RSN-127A.
6	^{235}U-fission chamber located in matrix position 138-37. Reuter-Stokes type RSN-34A-M1.
7	^{235}U-fission chamber located in matrix position 159-14. Reuter-Stokes type RSN-34A-M1.
8	^{235}U-fission chamber located in matrix position 153-15. Reuter-Stokes type RSN-34A-M1.
9	^{10}B-lined proportional counter located in matrix position 259-14. Reuter-Stokes type RSN-127A.
11	Sum of the 16 Na-can fission chambers.
13	Na-can fission chamber in 119-37.
14	Na-can fission chamber in 123-39.
15	Na-can fission chamber in 126-41.
16	Na-can fission chamber in 126-45.
17	Na-can fission chamber in 129-51.
18	Na-can fission chamber in 129-39.
19	Na-can fission chamber in 132-45.
20	Na-can fission chamber in 135-48.
21	Na-can fission chamber in 234-51.
22	Na-can fission chamber in 234-51 (behind 21).
23	Na-can fission chamber in 234-51 (behind 22).
24	Na-can fission chamber in 234-39.
25	Na-can fission chamber in 234-39 (behind 24).
26	Na-can fission chamber in 234-39 (behind 25).
27	Na-can fission chamber in 237-45.
28	Na-can fission chamber in 237-55.
29	Sum of detector No. 13, 14, 15, 16, 17, 18, 19, 20, 21, 24, 27, and 28.
30	Sum of detector No. 2, 3, 4, 5, and 6.

Table 4. Graphite Reference Case 1
Detection Efficiencies

Detector Number	Detector Locations	Detection Efficiency	Experimental Reactivity ($)
6	138-37	1.3346-6	-1.0015
7*	159-14	4.5838-8	
8	153-15	8.5299-8	
13	119-37	2.4846-7	
14	123-39	5.2579-7	
15	126-41	6.2960-7	
16	126-45	4.9937-7	
17	129-51	9.0791-7	
18	129-39	4.6506-7	
19	132-45	8.7975-7	
20	135-48	7.6626-7	
21	234-51	6.1078-7	
24	234-39	1.1737-6	
27	237-45	9.8533-7	
28	237-55	3.8854-7	
29	Sum	8.0802-6	
9**	259-14	1.5356-5	

* U^{235} SLFM detector.
** B^{10} SLFM detector.

Table 5. Case 2 Relative to Case 1

	Detector Locations	Detection Efficiency	Efficiency Ratio	Count Rate Ratio	Reactivity Inferred By Detector ($)	Best Estimate of Reactivity ($)	% DIFF
6	138-37	1.3314-6	0.9976	.9815	-0.9807	-.9797	0.10
7*	159-14	5.0308-8	1.0975	.8960	-0.9848		0.52
8	153-15	8.9350-8	1.0475	.9536	-0.9989		1.96
13	119-37	2.4747-7	0.9960	.9832	-0.9807		0.10
14	123-39	5.2358-7	0.9958	.9810	-0.9783		-0.14
15	126-41	6.2714-7	0.9961	.9814	-0.9790		-0.07
16	126-45	4.9727-7	0.9958	.9837	-0.9810		0.14
17	129-51	9.0488-7	0.9967	.9800	-0.9782		-0.15
18	129-39	4.6296-7	0.9955	.9801	-0.9772		-0.26
19	132-45	8.7664-7	0.9965	.9821	-0.9802		0.05
20	135-48	7.6330-7	0.9961	.9812	-0.9788		-0.09
21	234-51	6.0808-7	0.9956	.9809	-0.9780		-0.17
24	234-39	1.1706-6	0.9974	.9809	-0.9798		0.02
27	237-45	9.8214-7	0.9968	.9816	-0.9800		0.03
28	237-55	3.8686-7	0.9957	.9773	-0.9746		-0.52
29	Sum	8.0527-6	0.9966	.9815	-0.9797		0.0
9**	259-14	1.7259-5	1.1239	.8990	-1.0119		3.29

*U^{235} SLFM detector.
**B^{10} SLFM detector.

G. BORON BLADE EXPERIMENTS NEAR CRITICAL WITH POLYETHYLENE SLFM ZONE

The boron blade experiments near critical consisted of steps 23 through 26 of Table 2. Since step 26 was the least subcritical of all cases using polyethylene in the SLFM zone, it will be used as the reference configuration for all cases where polyethylene is used. The reference reactivity associated with this configuration is taken from the experimental results to be -.403 ($). Table 6 is a list of the detection efficiencies for configuration 26. These detection efficiencies will be used as reference values in the Modified Source Multiplication (MSM) calculations whenever polyethylene is used in the SLFM zone.

Tables 7, 8, and 9 are summaries of MSM calculations for configurations 23, 24, and 25 (Table 2) respectively. For reasons stated in Section C the reactivity inferred by detector 29 is assumed to be correct. As seen from these tables there is no problem in calculating reactivity using the SLFM detector if detection efficiency corrections are made. It should be noted that source effectiveness corrections have been considered and found to be negligible.

A comparison of steps 23 and 25 can be used to study spatial effects of blade insertion near critical. The detection efficiency of the SLFM detectors for both cases are normalized to the same level of subcriticality and compared. It is found that there is a spatial contribution of $\simeq$ 1.3% for the U^{235} fission detector and $\simeq$ 1.5% for the BF_3 detector. In other words, near critical, a boron blade inserted on the SLFM side of the core vs. a blade inserted on the opposite side of the core will result in a detection efficiency change of 1 to 2 percent at the SLFM location. Since

the count rate is directly proportional to the detection efficiency, similar changes in the count rate should be seen. However, it should be noted that the perturbations caused by boron blade insertions are very small and the numerical errors inherent in the calculations may be on the order of 1%. Thus, it is imperative that large perturbations be used in future experiments when spatial effects are being studied.

Hence, the net results of this part of the experiment are 1) SLFM detectors can be used to monitor reactivity near critical if detection efficiency corrections are applied, and 2) small spatial effects appear to be associated with absorber movement at subcriticality levels near critical for the mockup configuration.

Table 6. Case 26 Polyethylene Reference Detection Efficiencies

	Detector Locations	Detection Efficiency	Experimental Reactivity ($)
6	138-37	1.3385-6	−.403
7*	159-14	1.8762-7	
8	153-15	8.3534-8	
13	119-37	2.4934-7	
14	123-39	5.2768-7	
15	126-41	6.3179-7	
16	126-45	5.0117-7	
17	129-51	9.1078-7	
18	129-39	4.6677-7	
19	132-45	8.8261-7	
20	135-48	7.6884-7	
21	234-51	6.1301-7	
24	234-39	1.1771-6	
27	237-45	9.8840-7	
28	237-55	3.8995-7	
29	Sum	8.1074-6	
9**	259-14	5.7052-5	

*U^{235} SLFM detector.
**B^{10} SLFM detector.

Table 7. Case 23 Relative to Case 26

Detectors	Detection Efficiency	Efficiency Ratio	Count Rate Ratio	Calculated Reactivity ($)	Best Estimate of Reactivity ($)	% DIFF
6	1.3368-6	0.9987	3.1075	-1.2507	-1.2660	-1.21
7*	1.9180-7	1.0223	2.9886	-1.2313		-2.75
8	8.4963-8	1.0171	3.0048	-1.2316		-2.72
13	2.5224-7	1.0116	3.1035	-1.2652		-0.07
14	5.3209-7	1.0084	3.0960	-1.2582		-0.62
15	6.3272-7	1.0015	3.1124	-1.2562		-0.78
16	4.9798-7	0.9936	3.1786	-1.2728		0.53
17	9.0831-7	0.9973	3.2478	-1.3053		3.10
18	4.5919-7	0.9838	3.1143	-1.2347		-2.47
19	8.3474-7	0.9458	3.3311	-1.2708		0.38
20	7.3179-7	0.9518	3.3535	-1.2863		1.60
21	5.9923-7	0.9775	3.2415	-1.2769		0.86
24	1.1605-6	0.9859	3.1407	-1.2479		-1.44
27	9.2247-7	0.9333	3.3875	-1.2741		0.63
28	3.8702-7	0.9925	3.2092	-1.2836		1.39
29	7.9183-6	0.9767	3.2165	-1.2660		0.00
9**	5.8341-5	1.0226	2.9762	-1.2265		-3.12

*U^{235} SLFM detector.
**B^{10} SLFM Detector.

Table 8. Case 24 Relative to Case 26

Detectors	Detection Efficiency	Efficiency Ratio	Count Rate Ratio	Calculated Reactivity ($)	Best Estimate of Reactivity ($)	% DIFF
6	1.3319-6	0.9950	3.3289	-1.3348	-1.3271	0.58
7*	1.9128-7	1.0195	3.2352	-1.3292		0.15
8	8.5127-8	1.0191	3.2457	-1.3330		0.44
13	2.5441-7	1.0203	3.1959	-1.3141		-0.99
14	5.3796-7	1.0195	3.2031	-1.3160		-0.84
15	6.4311-7	1.0179	3.2072	-1.3156		-0.87
16	5.1016-7	1.0179	3.2144	-1.3186		-0.64
17	9.2411-7	1.0146	3.2362	-1.3232		-0.30
18	4.7468-7	1.0169	3.2279	-1.3228		-0.33
19	8.9186-7	1.0105	3.2541	-1.3252		-0.15
20	7.7528-7	1.0084	3.2992	-1.3407		1.02
21	6.2116-7	1.0133	3.2457	-1.3254		-0.13
24	1.1840-6	1.0058	3.2744	-1.3272		0.01
27	9.8517-7	0.9967	3.3378	-1.3407		1.02
28	3.9484-7	1.0126	3.3190	-1.3544		2.05
29	8.1968-6	1.0110	3.2573	-1.3271		0.00
9**	5.8166-5	1.0195	3.2154	-1.3211		-0.46

*U^{235} SLFM detector.
**B^{10} SLFM detector.

Table 9. Case 25 Relative to Case 26

Detectors	Detection Efficiency	Efficiency Ratio	Count Rate Ratio	Calculated Reactivity ($)	Best Estimate of Reactivity ($)	% DIFF
6	1.3026-6	.9732	2.9499	-1.1569	1.1382	1.64
7 *	1.8436-7	.9826	3.0303	-1.1998		5.42
8	8.1743-8	.9786	3.0460	-1.2013		5.54
13	2.4735-7	.9920	2.8458	-1.1377		-0.05
14	5.2307-7	.9913	2.8393	-1.1343		-0.35
15	6.2593-7	.9907	2.8369	-1.1326		-0.49
16	4.9699-7	.9917	2.8393	-1.1347		-0.31
17	9.0005-7	.9882	2.8377	-1.1301		-0.71
18	4.6308-7	.9921	2.8769	-1.1502		1.05
19	8.7271-7	.9888	2.8686	-1.1431		0.43
20	7.6066-7	.9894	2.8466	-1.1350		-0.29
21	6.0757-7	.9911	2.8177	-1.1254		-1.12
24	1.1577-6	.9835	2.8927	-1.1465		0.72
27	9.7461-7	.9860	2.8629	-1.1376		-0.06
28	3.8662-7	.9915	2.8522	-1.1397		0.12
29	8.0163-6	.9888	2.8563	-1.1382		0.00
9 **	5.6060-5	.9826	3.0211	-1.1963		5.10

*U^{235} SLFM detector.
**B^{10} SLFM detector.

H. CALIFORNIUM SOURCE EXPERIMENT NEAR CRITICAL

This experiment consisted of a series of steps (configurations 27 through 33 of Table 2) in which a CF^{252} source is moved on a traverse across the core. The purpose of this experiment is to determine the relative importance of a source due to spatial location.

For each step detection efficiency corrections were determined and used in the MSM equation with no source effectiveness corrections to determine subcriticality. The source effectiveness ratio is defined as:

$$\frac{S^i_{eff}}{S^o_{eff}} = \frac{\int_E\int_r \Phi^*(r,E)S^i(r,E)}{\int_E\int_r \Phi^*(r,E)S^o(r,E)}$$

where, $S^i(r,E)$ = inherent source of configuration i at position r and energy E and $S^o(r,E)$ - inherent source of reference configuration (step 26) at position r and energy E. This ratio was found and used in the MSM equation to determine the source corrected reactivity inferred by each detector. The resulting reactivities were then compared with the experimental reactivities in order to verify results. The calculations for steps 27 through 33 are summarized in Tables 10 through 16 respectively. It was found that the importance of the californium source varied from 1 to 13% due to spatial effects. Secondly, when the source corrections were applied the reactivities obtained agreed very well with the experimentally obtained reactivity.

At the same time it is observed that there is an increase in the SLFM detection efficiencies for both the U^{235} detector and the BF_3 detector as the source moves from the center to the edge of the core. This rise peaks as the source approaches the outer core-blanket interface. As the source moves into the blanket, the detection efficiency at the SLFM location

decreases. A maximum rise of 1 to 2 percent is seen in the detector efficiency. Since the count rate is proportional to both the source effectiveness and the detection efficiency, changes as much as 12% were observed in the detector count rate. Thus, if the source is being added or moved in the system at a near critical configuration, two important aspects must be considered: 1) importance of the inherent neutron source to the fission neutrons in the core multiplication, and 2) direct importance of the inherent neutron source to the SLFM detector response.

Table 10. Case 27 Relative to Case 26

Detectors	Detection Efficiency	Efficiency Ratio	Count Rate Ratio	Calculated Reactivity ($)	Calculated Reactivity with Source Correction ($)†	Experimental Reactivity ($)	% Diff.
6	1.3485-6	1.0075	2.2292	-.9051	-1.0236	-1.0015	2.21
7*	1.8713-7	0.9974	2.1867	-.8789	-0.9940		-0.75
8	8.3269-8	0.9968	2.1911	-.8802	-0.9954		-0.61
13	2.4820-7	0.9954	2.1867	-.8772	-0.9920		-0.95
14	5.2575-7	0.9963	2.1872	-.8782	-0.9931		-0.84
15	6.2994-7	0.9971	2.1964	-.8826	-0.9981		-0.34
16	4.9820-7	0.9941	2.1805	-.8736	-0.9879		-1.36
17	9.1192-7	1.0012	2.1911	-.8841	-0.9998		-0.17
18	4.6282-7	0.9915	2.2193	-.8868	-1.0029		0.14
19	8.7983-7	0.9969	2.2056	-.8861	-1.0021		0.06
20	7.6457-7	0.9945	2.2036	-.8832	-0.9988		-0.27
21	6.0806-7	0.9967	2.1887	-.8791	-0.9942		-0.73
24	1.1827-6	1.0048	2.2051	-.8929	-1.0098		0.83
27	9.8631-7	0.9979	2.2178	-.8919	-1.0086		0.71
28	3.8626-7	0.9905	2.2183	-.8855	-1.0014		-0.01
29	8.0846-6	0.9972	2.2026	-.8852	-1.0010		-0.05
9**	5.6904-5	0.9974	2.1782	-.8755	-0.9901		-1.13

†S_{eff} Ratio = 1.1309

*U^{235} SLFM detector.
**B^{10} SLFM detector.

Table 11. Case 28 Relative to Case 26

Detectors	Detection Efficiency	Efficiency Ratio	Count Rate Ratio	Calculated Reactivity ($)	Calculated† Reactivity with Source Correction ($)	Experimental Reactivity ($)	% Diff.
6	1.3405-6	1.0015	2.2952	-.9264	-1.0245	-1.0015	2.30
7 *	1.8843-7	1.0043	2.2406	-.9068	-1.0030		0.15
8	8.3973-8	1.0053	2.2517	-.9122	-1.0089		0.74
13	2.4768-7	0.9933	2.2326	-.8937	-0.9884		-1.30
14	5.2427-7	0.9935	2.2482	-.9001	-0.9955		-0.59
15	6.2761-7	0.9934	2.2538	-.9023	-0.9979		-0.36
16	4.9654-7	0.9908	2.2467	-.8971	-0.9922		-0.93
17	9.0766-7	0.9966	2.2492	-.9033	-0.9991		-0.24
18	4.6161-7	0.9890	2.2894	-.9124	-1.0092		0.77
19	8.7558-7	0.9920	2.2619	-.9043	-1.0001		-0.14
20	7.6157-7	0.9905	2.2691	-.9058	-1.0018		0.03
21	6.0637-7	0.9892	2.2558	-.8993	-0.9946		-0.69
24	1.1753-6	0.9985	2.2800	-.9175	-1.0147		1.32
27	9.8116-7	0.9927	2.2697	-.9080	-1.0043		0.28
28	3.8543-7	0.9884	2.2712	-.9047	-1.0006		-0.09
29	8.0508-6	0.9930	2.2650	-.9064	-1.0025		0.09
9 **	5.7299-5	1.0043	2.2292	-.9022	-0.9979		-0.36

†S_{eff} Ratio = 1.106

*U^{235} SLFM detector.
**B^{10} SLFM detector.

Table 12. Case 29 Relative to Case 26

Detectors	Detection Efficiency	Efficiency Ratio	Count Rate Ratio	Reactivity Inferred by Detectors ($)	Reactivity with Source Correction ($)	Experimental Reactivity ($)	% Diff.
6	1.3375-6	0.9993	2.3234	-.9357	-1.0230	-1.0015	2.15
7*	1.8868-7	1.0057	2.2743	-.9218	-1.0078		0.63
8	8.4222-8	1.0082	2.2635	-.9197	-1.0055		0.40
13	2.4766-7	0.9933	2.2635	-.9060	-0.9906		-1.09
14	5.2415-7	0.9933	2.2831	-.9139	-0.9992		-0.23
15	6.2740-7	0.9931	2.2712	-.9089	-0.9937		-0.77
16	4.9668-7	0.9946	2.2696	-.9097	-0.9946		-0.69
17	9.0661-7	0.9954	2.2836	-.9161	-1.0016		0.01
18	4.6199-7	0.9898	2.3137	-.9229	-1.0090		0.75
19	8.7544-7	0.9919	2.2931	-.9166	-1.0021		0.06
20	7.6179-7	0.9908	2.2936	-.9158	-1.0013		-0.02
21	6.0683-7	0.9899	2.2841	-.9112	-0.9963		-0.52
24	1.1732-6	0.9967	2.2889	-.9194	-1.0052		0.36
27	9.8080-7	0.9923	2.3143	-.9255	-1.0118		1.03
28	3.8581-7	0.9894	2.3052	-.9192	-1.0049		0.34
29	8.0484-6	0.9927	2.2915	-.9167	-1.0023		0.08
9**	5.7375-5	1.0057	2.2512	-.9124	-0.9975		-0.40

S_{eff} Ratio = 1.093

*U^{235} SLFM detector.
** B^{10} SLFM detector.

Table 13. Case 30 Relative to Case 26

Detectors	Detection Efficiency	Efficiency Ratio	Count Rate Ratio	Reactivity Inferred by Detectors ($)	Reactivity† with Source Correction ($)	Experimental Reactivity ($)	% Diff.
6	1.3349-6	0.9973	2.3574	-.9475	-1.0176	1.0015	1.61
7*	1.8909-7	1.0078	2.2889	-.9296	-0.9984		-0.31
8	8.4436-8	1.0108	2.2957	-.9352	-1.0044		0.29
13	2.4776-7	0.9937	2.3031	-.9223	-0.9905		-1.09
14	5.2430-7	0.9936	2.3127	-.9261	-0.9946		-0.69
15	6.2762-7	0.9934	2.2899	-.9167	-0.9846		-1.69
16	4.9725-7	0.9922	2.3073	-.9226	-0.9909		-1.06
17	9.0613-7	0.9949	2.3229	-.9314	-1.0003		-0.12
18	4.6278-7	0.9915	2.3419	-.9358	-1.0050		0.35
19	8.7620-7	0.9927	2.3261	-.9306	-0.9994		-0.21
20	7.6280-7	0.9921	2.3315	-.9322	-1.0011		-0.04
21	6.0785-7	0.9916	2.3063	-.9216	-0.9898		-1.17
24	1.1720-6	0.9957	2.3240	-.9325	-1.0015		0.0
27	9.8152-7	0.9930	2.3507	-.9407	-1.0103		0.88
28	3.8656-7	0.9913	2.3408	-.9351	-1.0043		0.28
29	8.0528-6	0.9933	2.3240	-.9303	-0.9991		-0.24
9**	5.7495-5	1.0078	2.2758	-.9243	-0.9927		-0.88

†S_{eff} Ratio = 1.074

*U^{235} SLFM detector.
**B^{10} SLFM detector.

Table 14. Case 31 Relative to Case 26

Detectors	Detection Efficiency	Efficiency Ratio	Count Rate Ratio	Reactivity Inferred by Detector ($)	Reactivity† with Source Correction ($)	Experimental Reactivity ($)	% Diff.
6	1.3341-6	0.9967	2.3770	-.9548	-1.0152	-1.0015	1.37
7*	1.8931-7	1.0090	2.3180	-.9426	-1.0023		0.08
8	8.4595-8	1.0127	2.3137	-.9443	-1.0041		0.26
13	2.4767-7	0.9933	2.3079	-.9239	-0.9824		-1.91
14	5.2406-7	0.9931	2.3375	-.9355	-0.9948		-0.68
15	6.2738-7	0.9930	2.3213	-.9289	-0.9878		-1.37
16	4.9712-7	0.9919	2.3310	-.9318	-0.9908		-1.07
17	9.0573-7	0.9945	2.3337	-.9353	-0.9945		-0.69
18	4.6269-7	0.9913	2.3574	-.9418	-1.0014		-0.01
19	8.7605-7	0.9926	2.3540	-.9416	-1.0013		-0.02
20	7.6268-7	0.9920	2.3469	-.9382	-0.9977		-0.38
21	6.0772-7	0.9914	2.3305	-.9311	-0.9901		-1.14
24	1.1715-6	0.9953	2.3419	-.9393	-0.9988		-0.27
27	9.8136-7	0.9929	2.3590	-.9439	-1.0037		0.22
28	3.8654-7	0.9912	2.3663	-.9452	-1.0051		0.36
29	8.0505-6	0.9930	2.3436	-.9379	-0.9973		-0.42
9**	5.7567-5	1.0090	2.2989	-.9348	-0.9940		-0.75

† S_{eff} = 1.063

*U^{235} SLFM detector.
**B^{10} SLFM detector.

Table 15. Case 32 Relative to Case 26

Detectors	Detection Efficiency	Efficiency Ratio	Count Rate Ratio	Reactivity Inferred by Detectors ($)	Reactivity† with Source Correction ($)	Experimental Reactivity ($)	% Diff.
6	1.3348-6	0.9972	2.4242	-.9742	-1.0162	1.0015	1.47
7 *	1.8886-7	1.0066	2.3702	-.9615	-1.0030		0.15
8	8.4314-8	1.0093	2.3590	-.9595	-1.0009		-0.06
13	2.4826-7	0.9957	2.3496	-.9428	-0.9835		-1.80
14	5.2533-7	0.9955	2.3697	-.9507	-0.9917		-0.98
15	6.2887-7	0.9954	2.3585	-.9461	-0.9869		-1.46
16	4.9856-7	0.9948	2.3702	-.9502	-0.9912		-1.03
17	9.0716-7	0.9960	2.3781	-.9545	-0.9957		-0.58
18	4.6421-7	0.9945	2.4085	-.9653	-1.0069		0.54
19	8.7815-7	0.9950	2.3975	-.9614	-1.0028		0.13
20	7.6478-7	0.9947	2.4004	-.9622	-1.0037		0.22
21	6.0966-7	0.9945	2.3747	-.9517	-0.9928		-0.87
24	1.1730-6	0.9963	2.3906	-.9598	-1.0012		-0.03
27	9.8352-7	0.9951	2.3969	-.9612	-1.0027		0.12
28	3.8778-7	0.9944	2.3987	-.9613	-1.0027		0.12
29	8.0693-6	0.9953	2.3866	-.9573	0.9986		-0.29
9 **	5.7429-5	1.0066	2.3540	-.9549	0.9961		-0.54

†S_{eff} Ratio = 1.043

*U^{235} SLFM detector.
**B^{10} SLFM detector.

Table 16. Case 33 Relative to Case 26

Detectors	Detection Efficiency	Efficiency Ratio	Count Rate Ratio	Reactivity with no Source Correction ($)	Reactivity† with Source Correction ($)	Experimental Reactivity ($)	% Diff.
6	1.3376-6	0.9994	2.5006	-1.0071	-1.0184	-1.0015	1.69
7*	1.8806-7	1.0023	2.4450	-0.9876	-0.9988		-0.27
8	8.3790-8	1.0031	2.4396	-0.9862	-0.9973		-0.42
13	2.4908-7	0.9990	2.4534	-0.9877	-0.9988		-0.27
14	5.2706-7	0.9988	2.4313	-0.9787	-0.9897		-1.18
15	6.3103-7	0.9988	2.4438	-0.9837	-0.9947		-0.67
16	5.0049-7	0.9987	2.4301	-0.9780	-0.9890		-1.24
17	9.0989-7	0.9990	2.4355	-0.9805	-0.9916		-0.99
18	4.6610-7	0.9986	2.4722	-0.9949	-1.0061		0.46
19	8.8151-7	0.9988	2.4691	-0.9939	-1.0051		0.36
20	7.6780-7	0.9986	2.4667	-0.9927	-1.0039		0.24
21	6.1211-7	0.9985	2.4343	-0.9796	-0.9906		-1.09
24	1.1762-6	0.9992	2.4752	-0.9967	-1.0079		0.64
27	9.8721-7	0.9988	2.4857	-1.0005	-1.0118		1.03
28	3.8941-7	0.9986	2.4685	-0.9934	-1.0046		0.31
29	8.0979-6	0.9988	2.4600	-0.9902	-1.0014		-0.01
9**	5.7185-5	1.0023	2.4301	-0.9816	-0.9927		-0.88

†S_{eff} = 1.011

*U^{235} SLFM detector.
**B^{10} SLFM detector.

I. BORON BLADE STEPS AT SHUTDOWN

To achieve the full shutdown state, all nineteen of the B_4C control rods were inserted. The boron blade steps performed at this state are steps 34 through 37 and are described in Table 2.

A slight error in the input data was made in the vicinity of detector 18 for all calculations. As a result data obtained by detector 18 is not a correct representation of the system and will not be reported. Also since detector 29 is dependent upon detector 18 the results of detector 29 must be redefined such that detector 18 is not included in the summation. A similar correction must also be applied to the reference data.

The results of the calculations for steps 34 through 37 are reported in Tables 17 through 20, respectively. As seen in these tables there are major changes in the detection efficiency for all four steps. Up to a 40% increase is seen in the detection efficiencies for the SLFM detectors. This implies that if the count rate with no efficiency corrections were used to infer reactivity, the reactivity inferred would be in error by 40%.

Although an experimentally determined reactivity is available for case 34, it was not used here for the following reasons. First, the experimentally obtained reactivities for steps 35 through 37 were not available. Thus, if the experimentally obtained reactivity was used in step 34, comparisons with any other step in this section would reflect inconsistent results. Secondly, a comparison between in-core detectors and SLFM detectors would be better illustrated if the reactivity inferred by detector 29 was calculated. Comparisons between experimental and calculated values will be done in Section K of this report.

A comparison of steps 34 and 36 can be used to determine spatial effects of a rod insertion at shutdown. The detection efficiency of the SLFM detectors are normalized to the same level of subcriticality and compared. A difference of 0.9% is observed for both the U^{235} detector and the B^{10} detector. Again the question is raised as to whether this small difference is an actual spatial effect or simply due to the inherent differences in the numerics. This determination can only be made if the large control rods are moved in future experiments to produce perturbations of the magnitude expected in the CRBRP.

Table 17. Case 34 Relative to Case 26

Detectors	Detection Efficiency	Efficiency Ratio	Count Rate Ratio	Reactivity Inferred by Detector	Reactivity[††] with Source Correction	Best Estimate of Reactivity	% Diff.
6	1.1683-6	.8728	93.458	-32.873	-34.418	-34.399	.06
7*	2.5495-7	1.3588	58.480	-32.023	-33.528		-2.53
8	1.1174-7	1.3377	61.350	-33.073	-34.627		.67
14	6.2027-7	1.1755	70.922	-33.598	-35.177		2.26
19	8.1196-7	.9200	88.496	-32.811	-34.353		-.13
20	8.0610-7	1.0485	78.125	-33.011	-34.563		.48
21	7.3438-7	1.1980	68.966	-33.296	-34.861		1.34
24	9.6233-7	.8175	100.000	-32.946	-34.494		.28
27	8.4104-7	.8509	97.087	-33.292	-34.857		1.33
28	5.3145-7	1.3629	61.728	-33.904	-35.497		3.19
29**	7.8985-6	1.0337	78.867	-32.855	-34.399		0.0
9[†]	7.7530-5	1.3589	58.140	-31.840	-33.336		-3.09

*U^{235} SLFM detector.

**Detector 29 does not contain data for detector 18. Reference values for detection efficiency and count rate without detector 18 data are 7.6406-6 and 5997.02, respectively.

[†]B^{10} SLFM detector.

[††]S_{eff} ratio = 1.047.

Table 18. Case 35 Relative to Case 26

Detectors	Detection Efficiency	Efficiency Ratio	Count Rate Ratio	Reactivity Inferred by Detectors	Reactivity†† with Source Correction	Best Estimate of Reactivity	% Diff.
6	1.1473-6	.8571	95.314	-32.922	-34.469	-34.601	-.38
7*	2.6237-7	1.3984	58.474	-32.953	-34.502		-.29
8	1.1430-7	1.3683	60.759	-33.504	-35.079		1.38
14	6.2107-7	1.1770	72.683	-34.476	-36.096		4.32
19	7.7430-7	.8773	94.637	-33.459	-35.032		1.24
20	7.7469-7	1.0076	84.810	-34.438	-36.057		4.21
21	7.2217-7	1.1780	70.686	-33.558	-35.135		1.54
24	9.3996-7	.7985	101.778	-32.753	-34.292		-.89
27	7.8744-7	.7967	103.674	-33.286	-34.850		.67
28	5.2861-7	1.3556	62.761	-34.287	-35.898		3.75
29**	7.7859-6	1.0190	80.475	-33.048	-34.601		0.0
9†	7.9780-5	1.3984	68.416	-32.921	-34.468		-.38

*U^{235} SLFM detector.

**Detector 29 does not contain data for detector 18. Reference values for detection efficiency and count rate without detector 18 data are 7.6406-6 and 5997.02, respectively.

†B^{10} SLFM detector.

††S_{eff} ratio = 1.047.

Table 19. Case 36 Relative to Case 26

Detectors	Detection Efficiency	Efficiency Ratio	Count Rate Ratio	Reactivity Inferred by Detectors	Reactivity[††] with Source Correction	Best Estimate of Reactivity	% Diff.
6	1.1386-6	.8506	96.894	-33.214	-34.775	-34.717	.16
7*	2.6175-7	1.3951	59.002	-33.173	-34.732		.04
8	1.1442-7	1.3698	60.927	-33.633	-35.214		1.43
14	6.2421-7	1.1829	71.756	-34.207	-35.815		3.16
19	8.0724-7	.9146	90.776	-33.459	-35.032		.90
20	8.0309-7	1.0445	81.227	-34.193	-35.800		3.18
21	7.3562-7	1.2000	69.098	-33.416	-34.987		.77
24	9.4591-7	.8036	101.778	-32.960	-34.509		-.60
27	8.2983-7	.8396	98.767	-33.418	-34.989		.78
28	5.3417-7	1.3698	62.633	-34.576	-36.201		4.27
29**	7.8732-6	1.0304	79.854	-33.159	-34.717		0.0
9[†]	7.9598-5	1.3952	58.649	-32.976	-34.526		-.55

*U^{235} SLFM detector.

**Detector 29 does not contain data for detector 18. Reference values for detection efficiency and count rate without detector 18 data are 7.6406-6 and 5997.02, respectively.

[†]B^{10} SLFM detector.

[††]S_{eff} ratio = 1.047.

Table 20. Case 37 Relative to Case 26

Detectors	Detection Efficiency	Efficiency Ratio	Count Rate Ratio	Reactivity Inferred by Detectors	Reactivity†† with Source Correction	Best Estimate of Reactivity	% Diff.
6	1.1434-6	.8542	96.214	-33.122	-34.679	-34.588	.26
7*	2.6113-7	1.3918	59.442	-33.341	-34.908		.92
8	1.1376-7	1.3618	62.306	-34.195	-35.802		3.51
14	6.2420-7	1.1829	71.642	-34.153	-35.758		3.38
19	8.0909-7	.9167	89.559	-33.086	-34.641		.15
20	8.0618-7	1.0486	80.505	-34.019	-35.618		2.98
21	7.3734-7	1.2028	69.378	-33.630	-35.211		1.80
24	9.4884-7	.8061	101.779	-33.063	-34.617		.08
27	8.3686-7	.8467	97.349	-33.217	-34.778		.55
28	5.3561-7	1.3735	62.252	-34.458	-36.078		4.31
29**	7.8926-6	1.0330	79.357	-33.035	-34.588		0.0
9†	7.9397-5	1.3916	59.930	-33.611	-35.191		1.74

*U^{235} SLFM detector.

**Detector 29 does not contain data for detector 18. Reference values for detection efficiency and count rate without detector 18 data are 7.6406-6 and 5997.02, respectively.

†B^{10} SLFM detector.

††S_{eff} ratio = 1.047.

J. CF^{252} EXPERIMENT IN THE FULL SHUTDOWN CONFIGURATION

This experiment was identical to the californium experiment described in Section H of this report except that this experiment was performed in the full shutdown configuration. The steps of this experiment are described as steps 38 thru 44 of Table 2. As in Section H, the reactivity inferred by each detector was determined using MSM methods without source corrections. Source effectiveness corrections were then calculated and applied to the reactivities obtained. The results were then compared with the experimentally obtained reactivity.

All calculations for steps 38 thru 44 are summarized in Tables 21 thru 27, respectively. As seen from each table the reactivities calculated agree favorably with the experimentally obtained reactivities. However, the most interesting features of these calculations are seen when a comparison is made between the results of the seven cases. It is found that as the source is moved from the core center to the edge of the core the effectiveness of the source is reduced by 8%. This compares with a 12% drop seen in the source experiment near critical. Thus, it is found that the source effectiveness is less dependent on spatial location at shutdown than at states close to critical, probably due to the decrease in the multiplication effect.

Table 21. Case 38 Relative to Case 26

Detectors	Detection Efficiency	Efficiency Ratio	Count Rate Ratio	Reactivity Inferred by Detectors	Reactivity†† with Source Correction	Experimentally Obtained Reactivity	% Diff.
6	1.2641-6	.9444	77.325	-29.428	-33.842	-33.700	.42
7*	2.4695-7	1.3162	54.440	-28.877	-33.208		-1.46
8	1.0702-7	1.2811	55.972	-28.897	-33.232		-1.39
14	5.9876-7	1.1347	65.680	-30.034	-34.539		2.49
19	8.0388-7	.9108	81.507	-29.917	-34.404		2.09
20	7.7614-7	1.0095	74.721	-30.400	-34.960		3.74
21	6.9350-7	1.1313	65.291	-29.767	-34.232		1.58
24	1.0290-6	.8742	86.525	-30.483	-35.055		4.02
27	8.4676-7	.8567	88.461	-30.541	-35.122		4.22
28	5.0007-7	1.2824	58.569	-30.269	-34.809		3.29
29**	7.6926-6	1.0068	72.638	-29.471	-33.892		.57
9†	7.5177-5	1.3177	53.990	-28.671	-32.972		-2.16

*U^{235} SLFM detector.

**Detector 29 does not contain data for detector 18. Reference values for detection efficiency and count rate without detector 18 data are 7.6406-6 and 5997.02, respectively.

†B^{10} SLFM detector.

††S_{eff} ratio = 1.145.

Table 22. Case 39 Relative to Case 26

Detectors	Detection Efficiency	Efficiency Ratio	Count Rate Ratio	Reactivity Inferred by Detectors	Reactivity†† with Source Correction	Experimentally Obtained Reactivity	% Diff.
6	1.2213-6	.9124	84.440	-31.050	-35.536	-33.700	5.45
7*	2.4976-7	1.3312	52.954	-28.404	-32.508		-3.54
8	1.1020-7	1.3192	53.851	-28.630	-32.767		-2.77
14	5.9336-7	1.1245	67.151	-30.431	-34.828		3.35
19	7.7887-7	.8825	84.998	-30.229	-34.597		2.66
20	7.6367-7	.9933	77.058	-30.846	-35.303		4.76
21	6.8466-7	1.1169	66.996	-30.156	-34.513		2.41
24	9.8102-7	.8334	92.906	-31.203	-35.712		5.97
27	8.1596-7	.8255	93.652	-31.156	-35.658		5.81
28	4.9384-7	1.2664	59.941	-30.591	-35.011		3.89
29**	7.6106-6	.9961	75.425	-30.278	-34.653		2.83
9†	7.5941-5	1.3311	52.382	-28.099	-32.159		-4.57

*U^{235} SLFM detector.

**Detector 29 does not contain data for detector 18. Reference values for detection efficiency and count rate without detector 18 data are 7.6406-6 and 5997.02, respectively.

†B^{10} SLFM detector.

††S_{eff} ratio = 1.144.

Table 23. Case 40 Relative to Case 26

Detectors	Detection Efficiency	Efficiency Ratio	Count Rate Ratio	Reactivity Inferred by Detectors	Reactivity†† with Source Correction	Experimentally Obtained Reactivity	% Diff.
6	1.1383-6	.8504	86.263	-29.564	-33.712	-33.700	.04
7*	2.5494-7	1.3588	52.760	-28.892	-32.966		-2.18
8	1.1384-7	1.3628	52.881	-29.042	-33.167		-1.58
14	5.6736-7	1.0752	68.794	-29.809	-34.012		.93
19	7.3910-7	.8374	86.195	-29.087	-33.188		-1.52
20	7.3846-7	.9605	76.895	-29.764	-33.961		.77
21	6.6361-7	1.0825	66.996	-29.228	-33.349		-1.04
24	9.0629-7	.7699	93.714	-29.078	-33.178		-1.55
27	7.8478-7	.7940	93.869	-30.036	-34.271		1.69
28	4.8785-7	1.2511	59.941	-30.221	-34.482		2.32
29**	7.8499-6	.9682	76.046	-29.673	-33.857		.47
9†	7.7726-5	1.3624	52.093	-28.601	-32.634		-3.16

*U^{235} SLFM detector.

**Detector 29 does not contain data for detector 18. Reference values for detection efficiency and count rate without detector 18 data are 7.6406-6 and 5997.02, respectively.

†B^{10} SLFM detector.

††S_{eff} ratio = 1.141.

Table 24. Case 41 Relative to Case 26

Detectors	Detection Efficiency	Efficiency Ratio	Count Rate Ratio	Reactivity Inferred by Detectors	Reactivity[††] with Source Correction	Reactivity from Case 34	% Diff.
6	1.1221-6	.8383	88.265	-29.819	-33.679	-33.700	.06
7*	2.6332-7	1.4035	51.771	-29.282	-33.073		-1.86
8	1.1737-7	1.4050	52.069	-29.482	-33.299		-1.19
14	5.9092-7	1.1198	68.479	-30.903	-34.904		3.57
19	7.6303-7	.8645	86.806	-30.243	-34.158		1.36
20	7.5714-7	.9848	77.743	-30.854	-34.848		3.41
21	6.8957-7	1.1249	67.180	-30.455	-34.398		2.07
24	9.1528-7	.7776	94.078	-29.481	-33.298		-1.19
27	7.9170-7	.8010	95.521	-30.835	-34.827		3.34
28	5.0061-7	1.2838	60.059	-31.073	-35.096		4.14
29**	7.4669-6	.9773	76.434	-30.104	-34.001		.89
9[†]	8.0078-5	1.4036	51.266	-28.999	-32.753		-2.81

*U^{235} SLFM detector.

**Detector 29 does not contain data for detector 18. Reference values for detection efficiency and count rate without detector 18 data are 7.6406-6 and 5997.02, respectively.

[†]B^{10} SLFM detector.

[††]S_{eff} ratio = 1.129.

Table 25. Case 42 Relative to Case 26

Detectors	Detection Efficiency	Efficiency Ratio	Count Rate Ratio	Reactivity Inferred by Detectors	Reactivity†† with Source Correction	Reactivity from Case 34	% Diff.
6	1.1246-6	.8402	89.125	-30.178	-34.197	-33.700	1.47
7*	2.6321-7	1.4029	51.107	-28.894	-32.739		-2.85
8	1.1757-7	1.4074	52.254	-29.638	-33.587		-.34
14	5.8922-7	1.1166	69.324	-31.196	-35.347		4.89
19	7.6017-7	.8613	87.530	-30.381	-34.424		2.15
20	7.5299-7	.9794	78.509	-30.987	-35.110		4.18
21	6.8482-7	1.1171	67.553	-30.413	-34.460		2.26
24	9.1691-7	.7790	96.104	-30.169	-34.183		1.43
27	7.8908-7	.7983	95.409	-30.696	-34.781		3.21
28	4.9672-7	1.2738	59.825	-30.710	-34.796		3.25
29**	7.4424-6	.9741	77.083	-30.259	-34.285		1.74
9†	8.0039-5	1.4029	51.586	-29.165	-33.046		-1.94

*U^{235} SLFM detector.

**Detector 29 does not contain data for detector 18. Reference values for detection efficiency and count rate without detector 18 data are 7.6406-6 and 5997.02, respectively.

†B^{10} SLFM detector.

††S_{eff} ratio = 1.133.

Table 26. Case 43 Relative to Case 26

Detectors	Detection Efficiency	Efficiency Ratio	Count Rate Ratio	Reactivity Inferred by Detectors	Reactivity[††] with Source Correction	Reactivity from Case 34	% Diff.
6	1.1952-6	.8929	90.479	-32.559	-35.905	-33.700	6.66
7*	2.5530-7	1.3607	53.189	-29.167	-32.200		-4.45
8	1.1354-7	1.3592	53.136	-29.106	-32.133		-4.65
14	6.0016-7	1.1374	70.408	-32.272	-35.628		5.72
19	7.8550-7	.8900	86.909	-31.171	-34.412		2.12
20	7.7134-7	1.0033	77.934	-31.509	-34.786		3.22
21	6.9245-7	1.1296	67.553	-30.752	-33.950		.74
24	9.7360-7	.8271	98.471	-32.823	-36.237		7.53
27	8.2194-7	.8316	95.075	-31.862	-35.176		4.38
28	4.9961-7	1.2812	60.143	-31.054	-34.284		1.73
29**	7.6577-6	1.0022	77.451	-31.281	-34.534		2.48
9[†]	7.7632-5	1.3607	52.942	-29.032	-32.051		-4.89

*U^{235} SLFM detector.

**Detector 29 does not contain data for detector 18. Reference values for detection efficiency and count rate without detector 18 data are 7.6406-6 and 5997.02, respectively.

[†]B^{10} SLFM detector.

[††]S_{eff} ratio = 1.104.

Table 27. Case 44 Relative to Case 26

Detectors	Detection Efficiency	Efficiency Ratio	Count Rate Ratio	Reactivity Inferred by Detectors	Reactivity†† with Source Correction	Experimentally Obtained Reactivity	% Diff.
6	1.1798-6	.8814	92.453	-32.840	-34.876	-33.700	3.49
7*	2.5860-7	1.3783	56.142	-31.184	-33.117		-1.73
8	1.1529-7	1.3802	56.115	-31.212	-33.147		-1.64
14	5.9232-7	1.1225	71.414	-32.306	-34.309		1.80
19	7.9964-7	.9060	88.161	-32.190	-34.186		1.44
20	7.9552-7	1.0347	78.610	-32.778	-34.810		3.29
21	7.1085-7	1.1596	69.182	-32.331	-34.336		1.89
24	9.7358-7	.8271	99.277	-33.092	-35.143		4.28
27	8.3411-7	.8439	97.466	-33.148	-35.203		4.46
28	5.1934-7	1.3318	61.014	-32.746	-34.776		3.19
29**	7.8133-6	1.0226	78.290	-32.265	-34.265		1.68
9†	7.8247-5	1.3715	55.882	-30.886	-32.801		-2.67

*U^{235} SLFM detector.

**Detector 29 does not contain data for detector 18. Reference values for detection efficiency and count rate without detector 18 data are 7.6406-6 and 5997.02, respectively.

†B^{10} SLFM detector.

††S_{eff} ratio = 1.062.

K. COMPARISON OF CALCULATED AND EXPERIMENTAL RESULTS

Two types of comparisons were made between calculated and experimental results. First, a comparison was made between the experimental and calculated ratio of the SLFM detector response (detector 7) to the in-core detector response (detector 6). These comparisons are shown in Table 28. It was found that with graphite in the SLFM zone, (cases 1, 2, 61, and 62) the C/E ratios range from 1.09 to 1.145. This agrees favorably with the results of the U^{235} foil experiment where a similar C/E was found to be 1.137. With polyethylene in the SLFM zone (cases 23 through 44), the C/E ratios range from $\sim$ 1.20 to 1.24. These results imply that there is a systematic error of $\sim$ 14% associated with the use of graphite in the SLFM zone and an error of $\sim$ 21% associated with the use of polyethylene in the SLFM zone. Similar errors have been observed in other calculations and appear to be due to the lack of sufficient discrete energy groups in the low energy range. The 44 energy group structure used for these calculations had 6 energy groups below 450 eV. When similar calculations were made with polyethylene in the SLFM zone using a 51 energy group structure with 11 energy groups below 450 eV, C/E values of $\sim$ 1.10 were obtained. Thus, it is possible that with the proper treatment of the low energy spectrum, C/Es approaching 1.0 can be obtained.

The second comparison between experimental and calculated results is a comparison of calculated reactivities from MSM methods with experimentally obtained reactivities. This comparison was made for selected cases and is shown in Table 29. Using MSM methods all systematic errors cancelled and as can be seen, the C/Es obtained were very good. It should be noted that from this table it appears that the SLFM detectors

infer more accurate results than the in-core detector. This is strictly a coincidence. As in other SLFM experiments the SLFM detectors infer levels of subcriticality that are slightly less than the in-core detector.[4] Thus, by coincidence, the reactivities inferred by the SLFM detectors appear to be closer to the actual experimentally obtained reactivities.

Table 28. Comparison of Calculated Count Rate Ratios with Experimentally Obtained Count Rate Ratios

Case Number	Calculated Ratio: Detector 7 Response / Detector 6 Response	Experimental Ratio: Detector 7 Response / Detector 6 Response	C/E
1	.0343	.0301	1.140
2	.0378	.0330	1.145
23	.1433	.1182	1.212
24	.1436	.1170	1.227
25	.1415	.1107	1.278
26	.1402	.1137	1.233
27	.1388	.1159	1.198
28	.1406	.1165	1.207
29	.1411	.1162	1.214
30	.1417	.1171	1.210
31	.1419	.1166	1.217
32	.1414	.1163	1.216
33	.1406	.1163	1.209
34	.2182	.1820	1.199
35	.2287	.1854	1.234
36	.2299	.1868	1.231
37	.2284	.1841	1.241
38	.1953	.1615	1.209
39	.2045	.1814	1.127
40	.2240	.1860	1.204
41	.2347	.1939	1.210
42	.2340	.1983	1.180
43	.2136	.1935	1.104
44	.2192	.1873	1.170
61	.0528	.0483	1.093
62	.0425	.0390	1.090

Table 29. Comparison of Calculated and Experimentally Obtained Reactivities for Selected Cases

Case Number	Experimental Reactivity from Detector 29 Data	Calculated Reactivity Using Detector 6 Data and MSM Methods		Calculated Reactivity Using Detector 7 Data and MSM Methods		Calculated Reactivity Using Detector 9 Data and MSM Methods	
		($)	C/E	($)	C/E	($)	C/E
27	-1.0015	-1.0236	1.022	-.9940	.993	-.9901	.989
28	-1.0015	-1.0245	1.023	-1.0030	1.001	-.9979	.996
29	-1.0015	-1.0230	1.021	-1.0078	1.006	-.9975	.996
30	-1.0015	-1.0176	1.016	-.9984	.997	-.9927	.991
31	-1.0015	-1.0152	1.014	-1.0023	1.001	-.9940	.993
32	-1.0015	-1.0162	1.015	-1.0030	1.001	-.9961	.995
33	-1.0015	-1.0184	1.017	-.9988	.997	-.9927	.991
34	-33.770	-34.418	1.021	-33.528	.995	-33.336	.989
38	-33.700	-33.842	1.004	-33.208	.985	-32.972	.978
39	-33.700	-35.536	1.054	-32.508	.965	-32.159	.954
40	-33.700	-33.712	1.001	-32.966	.978	-32.634	.968
41	-33.700	-33.679	.999	-33.073	.981	-32.753	.972
42	-33.700	-34.194	1.015	-32.739	.971	-33.046	.981
43	-33.700	-35.905	1.065	-32.200	.955	-32.051	.951
44	-33.700	-34.876	1.035	-33.117	.983	-32.801	.973

L. DIFFUSION THEORY CALCULATIONS

As a part of this analysis a diffusion calculation was made to obtain a transport-diffusion comparison. The U^{235} foil traverse experiment was used to calculate the U^{235} foil reaction rates. These results were then compared with both the experimental results and the results calculated using transport theory as shown in Table 30. From this it is seen that there was excellent agreement in the core, good agreement in the reflector and poor agreement in the graphite region. There was approximately a 50% error in the calculation of the U^{235} reaction rate at the SLFM location. However, from previous experience this appears to be mostly a systematic error. As in the case of the transport calculations when MSM methods are used, the systematic errors disappeared. It is probable that diffusion methods will give adequate results for penetration calculations of this type if MSM methods are used.

Table 30. Comparison of Transport and Diffusion Calculations for the U-235 Foil Experiment

Experiment	Transport	C/E	Diffusion	C/E	Diffusion / Transport
1.0	1.0	1.0	1.0	1.0	1.0
.8849	.9012	1.018	.8939	1.010	.992
.7247	.7481	1.032	.7477	1.032	.999
.5629	.5801	1.031	.5826	1.035	1.004
.4472	.4529	1.013	.4491	1.004	.992
.3577	.3700	1.034	.3710	1.037	1.003
.2768	.2847	1.029	.2857	1.032	1.004
.2116	.2075	.981	.2043	.966	.985
.1733	.1780	1.027	.1719	.992	.966
.1860	.1805	.970	.1726	.928	.956
.1623	.1571	.968	.1540	.949	.981
.1163	.1155	.993	.1098	.944	.951
.0758	.0792	1.045	.0744	.982	.939
.0464	.0473	1.022	.037	.797	.782
.0310	.0352	1.135	.027	.871	.767
.0336	.0382	1.137	.050	1.488	1.309
.0246	.0254	1.033	.0381	1.549	1.500
.0103	.0097	.942	.0099	.961	1.021

M. CONCLUSIONS

In summary, the following information has been obtained from this analysis:

1. For the mockup critical there was no problem in calculating the reactivity level if MSM methods were used.
2. Near critical spatial effects of absorber insertions were observed. However, since the perturbations were so small it was difficult to determine whether the differences observed were spatial effects or simply differences in numerics.
3. Near critical, two types of spatial effects due to source movement were observed. First of all, the fission rate was affected which indirectly affected the detector response. Secondly, the direct contribution of the source to the detector response was affected by the source movement. For the particular source movement performed, the two spatial effects tended to cancel each other which resulted in only a 11% change in the SLFM detector count rate. If the source movement had been performed on the other side of the core, no cancelling effects would occur and the change in SLFM count rate would have been much larger.
4. In going from near critical to approximately -34($), as much as a 40% change in detection efficiency was observed.
5. At shutdown ($\sim$ -34$), as in the near critical calculations, spatial effects due to absorber insertions were observed. The only difference was that changes observed were even smaller at shutdown than they were in the near critical calculations.

6. Similarly, at shutdown, spatial effects due to source movement were observed, but on a much smaller basis than in the near critical calculations.
7. With graphite in the SLFM zone it was found that the absolute count rates calculated for the SLFM detector were ∿14% high compared to the experiment. Similarly, with polyethylene in the SLFM zone the absolute count rates calculated were ∿21% high. It was determined that the majority of this over-prediction was due to poor group resolution of the low energy spectrum.
8. When diffusion theory was used instead of transport theory, the absolute count rates obtained were much worse. However, it appears that the differences observed are systematic and when used in MSM calculations, diffusion theory seems to be adequate. It should be noted that this has only been shown to be true for the type of penetrations observed in this experiment. It has yet to be shown whether or not the errors associated with the use of diffusion theory remain systematic when the calculations require calculating deep penetrations through sodium and steel as in the actual CRBR design.

Thus, much information has been obtained but, as stated in the introduction, the experiment is non-prototypic of the CRBR design and the results from this experiment may be non-prototypic. Hence, it is imperative that a full mock-up experiment be performed on the expanded ZPPR matrix. It is hoped that the experiment will be designed in such a way that prototypic SLFM responses for normal and abnormal reactor operations can be observed.

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