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Development Report
UC-81, Reactors-Power
(Special Distribution)

MASTER

**SUMMARY NUCLEAR
CALCULATIONS FOR THE
SM-2 CORE 1**

ALCO PRODUCTS, INC.

NUCLEAR POWER ENGINEERING DEPARTMENT
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SUMMARY NUCLEAR CALCULATIONS
FOR THE SM-2 CORE I

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ABSTRACT

This report presents the results of a limited analysis of the Extended SM-2 Critical Experiments. A review of the analytical models is presented to ascertain the accuracy of the reactivity calculations for the reference SM-2 Core I. A new reference B-10 loading was derived based on analysis and experimental measurements. Calculations of power distributions and burnup behavior of the reference core are presented and comparisons to available measured data are made.

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SUMMARY

This report contains a summary of the nuclear calculations of the SM-2 Core I which have been performed since issuance of the final design report, APAE No. 69. (1) Primary emphasis has been placed upon a limited analysis of the SM-2 Flexible Critical Experiments. (2)

A review of the analytical models was made in an effort to ascertain the accuracy of the predicted nuclear behavior of the reference SM-2 core. Calculations of core excess reactivity, percent of thermal fissions, and power distributions for the experimental mockup core were made and compared to measured data. It was found that by using modified two-group theory with thermal parameters calculated by P₃ theory, employing thermal microscopic cross sections averaged over a hardened Maxwell-Boltzmann neutron energy distribution, the best agreement with measured data was obtained by using fast parameters calculated by the MUFT-III code with a P-1 slowing down approximation. Predictions of excess reactivities of the SM-2 reference core should be accurate to about $\pm 1.0\% \rho$.

The maximum reactivity to be controlled (at midlife) is predicted to be $18.3 \pm 1.0\% \rho$, with a safety margin of about $4.5\% \rho$ with all seven control rods fully inserted. The minimum lifetime of the reference core is expected to be 28.7 MWYRS. The best estimates of the temperature coefficient are $-0.35 \times 10^{-4} \Delta K/^{\circ}F$ and $-3.3 \times 10^{-4} \Delta K/^{\circ}F$ at $68^{\circ} F$ and $510^{\circ} F$, respectively. Based upon a combination of analytical predictions and measured reactivity effects, a final reference B-10 loading was determined. The best estimates for the final loadings for the reference SM-2 core are 36.3 kg and 53.1 gms for U-235 and B-10, respectively.

A detailed analysis was made of the power distribution of the experimental mockup core, including the effects of the flow divider and the laminated steel reflector. The analysis verified that the power peaking factors for the SM-2 reference core, as reported in APAE Memo 286 (3), may be considered conservative for thermal calculations.

In general, the agreement between calculations and measurements for the SM-2 experimental core is quite good. In addition, calculations of the burnup behavior of the SM-1 Core I by the same techniques described in this report, agree well with measurements. Therefore, it is felt that confidence may be expressed in the predicted nuclear behavior of the reference SM-2 core. To further reduce possible uncertainties in the analytical predictions, recommendations in regard to additional measurements and analysis are presented.

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1.0 INTRODUCTION

The nuclear design of the reference SM-2 core, as of July 1, 1960, was presented in APAE No. 69. ⁽¹⁾ However, certain aspects of the design were not completed at the end of the contract period. Probably the most significant of these, from the nuclear standpoint, were the extended SM-2 critical experiments as reported in APAE No. 54, Supplement 1. ⁽²⁾ The latter report contains data obtained from a hot mockup core including power distributions with the core containing a flow divider, effects of integral flux suppressors, a summary of boron analyses, and several other pertinent measurements.

With the availability of these new measurements, additional nuclear calculations were performed to determine the effect upon the predicted nuclear behavior of the reference SM-2 core. This report, together with APAE Memo 286, ⁽³⁾ "Flux and Power Distributions for the SM-2 Reference and Critical Experiment Cores", and AP Note 366, "Analysis of Reactivity, Burnup, and Lifetime for the SM-2 Reference Core," ⁽⁴⁾ summarize the nuclear calculations performed since issuance of the SM-2 design report, APAE No. 69. ⁽¹⁾

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2.0 REVIEW OF ANALYTICAL MODELS

In order to obtain better agreement between calculated and measured core reactivities, a detailed review of the analytical methods employed at Alco was initiated. Previous analytical models were underestimating measured reactivities by 1.5 to 2.0% ρ .⁽⁵⁾ One major uncertainty was the approximation used in the solution of the slowing down equations in the MUFT-III code. It was shown previously in APAE No. 27⁽⁵⁾ pg. 50, that the P-1 slowing down approximation gave the best check with the measured data and was 1.5% ρ higher than the P-1 S.G. approximation. However, since P-1 S.G. predicted what was then the measured neutron age in water (30-33 cm²), it was considered to be the best available analytical model.

Since that time, the measured age in water has steadily decreased to a present value of 26-29 cm². Ages predicted by the P-1 model agree with these values. Therefore, a thorough check of the MUFT-III model was made to determine the best slowing down approximation in the light of more recent data.

Another source of uncertainty exists in the stainless steel microscopic cross-section file used in the MUFT-III code. After a careful study of the cross-section used in the stainless steel file, including comparisons with files used by WAPD⁽⁶⁾ and Phillips⁽⁷⁾, a revision of this file was issued. Changes were made in the scattering and inelastic scattering cross sections.

The thermal model is adequate for reactivity calculations since any change in the hardening factor or neutron distribution will not make a significant reactivity change. A Maxwellian hardened distribution is assumed in the microscopic thermal cross-section calculations.

2.1 REACTIVITY CALCULATIONS

Reactivity calculations were performed on the SM-2 experimental core at 68° F and on the SM-2 reference core at 68° F and 510° F.

Additional reactivity calculations on the SM-1 Core I and on various critical arrays were performed under Task 2.3 of the PWR Support Program.⁽⁸⁾ These calculations showed that the MUFT-III, P-1, 59 group model predicted the reactivity of the SM-1 core to within one-half percent. Table 2.1 shows similar results for the reactivity of the SM-2 cores. Reactivities predicted by the MUFT-III, P-1 S.G. model are much lower. This was the primary basis for selection of the MUFT-III, P-1 model.

TABLE 2.1

SUMMARY OF REACTIVITY CALCULATIONS
ON THE SM-2 REFERENCE AND EXPERIMENTAL CORES

<u>Calculational Model</u>	<u>Calculated - % ρ</u>	<u>(Calc. - Meas.) % ρ</u>
<u>SM-2 Exp. Core - 68° F</u>		
M-III, P-1, 59 gps.	12.39	- 0.58
M-III, P-1 S.G., 59 gps.	10.67	- 2.30
<u>SM-2 Ref. Core - 68° F</u>		
M-III, P-1, 59 gps.	14.89	- 0.69
M-III, P-1 S.G., 59 gps.	13.26	- 2.32
<u>SM-2 Ref. Core - 510° F</u>		
M-III, P-1, 58 gps.	8.98	-
M-III, P-1 S.G., 58 gps.	7.16	-

MEASURED - % ρ

SM-2 Experimental Core - 68° F
 Measured (All Fixed Elements,
 H₂O Reflected) = 12.97% using $\beta_{\text{eff}} = 0.0078$

SM-2 Reference Core - 68° F
 (All Fixed Elements) = 15.58% measured extrapolated.

2.2 PERCENT OF THERMAL FISSIONS (β)

The percent of thermal fissions in the SM-2 core was calculated and compared to measurements to check the balance of fast and thermal fissions in the analytical model.

Measurements were made on the SM-2 experimental core using bare and cadmium covered fission foils from which the cadmium fraction was obtained. The cadmium fraction is essentially the ratio of fast to total fissions; therefore:

$$1 - C.F. = \beta$$

Where C.F. = Cadmium fraction or fraction of fast fission

β = fraction of thermal fissions.

This equation would be exact if the cadmium energy was at the effective thermal neutron energy. The effective cadmium energy is about 0.4 ev.

Calculations were made of the fraction of thermal neutrons as a function of cutoff energy by using different numbers of fast groups in the MUFT-III code (different energy cutoffs). It can be seen from Table 2.2 that the fraction of thermal fissions decreases as the cutoff energy decreases. Since the measurements were made with cadmium covered foils, which have an effective cutoff energy of about 0.4 ev, the 56 group calculation should predict the value more accurately. This is verified by the results presented in Table 2.2.

TABLE 2.2

PERCENT THERMAL FISSIONS (β) IN THE SM-2 CORE, 68°F.

<u>No. of Groups Used in the MUFT-III Code</u>	<u>Cutoff Energy (ev.)</u>	<u>β Calc.</u>	<u>Meas./ β Calc.</u>
P-1, 54 groups	0.625	0.75	0.93
P-1, 56 groups	0.400	0.72	0.97
P-1, 59 groups	0.196	0.65	1.08
P-1, S.G., 59 groups	0.196	0.65	1.08

β measured = 0.70 in SM-2 Experimental Core, 68° F

2.3 GROSS POWER DISTRIBUTION THROUGH CORE

As shown in Fig. 2.1, the calculated gross power distribution through the SM-2 core is in reasonably good agreement with the measured values for both the steel and water reflected cases. The calculated power distribution for the steel reflected core seems to drop off faster than the measured points

near the core edge for the case where the Alco stainless steel fast cross-section files were used in the steel reflector. Agreement is better when the MUFT-V steel files, obtained from Phillips, were used in the steel reflector. This is probably due to the relatively large absorption cross-section used in the Alco steel files.

2.4 REFERENCE NUCLEAR PARAMETERS

As a result of investigation of the analytical models for agreement with measured reactivity and power distributions, a tabulation of what is now considered the best available nuclear parameters was obtained for the SM-2 reactor. Nuclear constants for the SM-2 experimental and reference cores, water, steel, and the europium dioxide flux suppressors, both at 68⁰ F and 510⁰ F, are listed in Tables 2.3, 2.4, 2.5, and 2.6. These numbers reflect the best estimate of the material content in the SM-2 reference and experimental cores as well as the latest cross-section files and will be valuable for any future calculations on the SM-2.

2.1 Relative Radial Power Distribution Through Center of SM-2 Core, 68° F.

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TABLE 2.3

SM-2 EXPERIMENTAL CORE - 68° F

From Codes M-III, P-1, 59 gps. - Rev. S.S. Files

Parameter	Units	F.E. - 68° F	S.S. - 68° F	H ₂ O - 68° F
D _f	cm	1.251106	1.507169	1.299072
τ	cm. ²	32.015349	185.296199	27.781769
Σ _T ^f	cm. ⁻¹	0.039078	0.008134	0.046760
Σ _a ^f	cm. ⁻¹	0.015555	0.008134	0.000655
Σ _{sℓ}	cm. ⁻¹	0.023523	-	0.046105
νΣ _f ^f	cm. ⁻¹	0.019669	-	-
K _f		1.264480	-	-
P		0.601949	0.000002	0.986002
D _{th}	cm.	0.163563	0.311171	0.172304
Σ _a th	cm. ⁻¹	0.414939	0.193228	0.016960
νΣ _f th	cm. ⁻¹	0.611276	-	-
K _{th}		1.473170	-	-
L ²	cm. ²	0.394187	1.610382	10.159433
g'		0.821059	-	-
Σ _a ^{sub}	cm. ⁻¹	0.015342	-	-
Σ _P (7 rods)	cm. ⁻¹	0.211640	-	-

TABLE 2.4

SM-2 REFERENCE CORE - 68° F

From Codes M-III, P-1, 59 gps. - Rev. S.S. Files

Parameter	Units	F.E. - 68° F	S.S. - 68° F	H ₂ O - 68° F
D _f	cm	1.221576	1.507169	1.299072
τ	cm. ²	30.705575	185.296199	27.781769
Σ_T^f	cm. ⁻¹	0.039784	0.008134	0.046760
Σ_a^f	cm. ⁻¹	0.015257	0.008134	0.000655
Σ_{sl}	cm. ⁻¹	0.024527	-	0.046105
$v\Sigma_f^f$	cm. ⁻¹	0.019581	-	-
K _f		1.283410	-	-
P		0.616490	0.000002	0.986002
D _{th}	cm.	0.160840	0.311171	0.172304
Σ_a^{th}	cm. ⁻¹	0.430834	0.193228	0.016960
$v\Sigma_f^{th}$	cm. ⁻¹	0.647359	-	-
K _{th}		1.502573	-	-
L ²	cm ²	0.373322	1.610382	10.159433
g'		0.885699	-	-
Σ_a^{sub}	cm. ⁻¹	0.016012	-	-
$\Sigma_P^{(7 \text{ rods})}$	cm. ⁻¹	0.219015	-	-

TABLE 2.5

SM-2 REFERENCE CORE - 510°F

From Codes M-III, P-1, 58 gps., Rev. S.S. Files

Parameter	Units	F.E. - 510°F	S.S. - 510°F	H ₂ O - 510°F
D _f	cm.	1.454769	-	1.662733
τ	cm. ²	45.816365	-	45.761083
Σ _T ^f	cm. ⁻¹	0.031752	0.00813	0.036335
Σ _a ^f	cm. ⁻¹	0.013635	0.00813	0.000465
Σ _{sl}	cm. ⁻¹	0.018117	-	0.035870
νΣ _f ^f	cm. ⁻¹	0.017419	-	-
K _f		1.277521	-	-
P		0.570576	-	0.987210
D _{th}	cm.	0.246522	0.326055	0.297148
Σ _a th	cm. ⁻¹	0.322387	0.144415	0.009947
νΣ _f th	cm. ⁻¹	0.484027	-	-
K _{th}		1.501384	-	-
L ²	cm ²	0.764676	2.257764	29.873127
g'		0.933543	-	-
Σ _a ^{sub}	cm. ⁻¹	0.011314	-	-
Σ _p ^(7 rods)	cm. ⁻¹	0.192456	-	-
Σ _{axe}	cm. ⁻¹	0.016168	-	-

TABLE 2.6

EUROPIUM FLUX SUPPRESSOR CONSTANTS FOR THE SM-2
REFERENCE CORE

From Codes MUFT-III P-1 & P-3, 58 & 59 gps.

<u>Parameter</u>	<u>Units</u>	<u>68⁰ F</u>	<u>510⁰ F</u>
τ	cm. ²	24.241161	34.510610
D_f	cm.	1.172583	1.372437
Σ_T^f	cm. ⁻¹	0.048372	0.039769
Σ_a^f	cm. ⁻¹	0.046117	0.038246
Σ_{sl}	cm. ⁻¹	0.002255	0.001523
$\nu \Sigma_f^f$	cm. ⁻¹	-	-
P		0.046607	0.038280
D_{th}	cm.	0.107199	9.146397
Σ_a^{th}	cm. ⁻¹	1.358379	1.231539
L^2	cm ²	0.078917	0.118874
g'		0.297581	0.509634

3.0 ROD WORTH AND BANK POSITION

The seven-rod bank in SM-2 was calculated by use of the homogeneous thermal absorption cross-section model which simulates the control rod bank (called the Σ_p Method). This cross-section is obtained by normalizing the calculated reactivity to the measured shutdown reactivity as described in APAE No. 32.⁽⁹⁾ This method is therefore dependent on either the measured integral rod bank worth or the measured shutdown reactivity.

3.1 INTEGRAL SEVEN-ROD BANK WORTH

Figure 3.1 shows the calculated and measured integral seven-rod bank worth for the SM-2 experimental core at 68° F. The calculated integral curve was obtained by running a series of axial VALPROD calculations using the Σ_p method. The poison cross-section was inserted in 2-in. steps into the core until the entire core was poisoned. Since the curve was normalized to the total measured rod worth, it is not surprising that the curves meet at the top of the core. However, the shape of the calculated rod worth curve is in good agreement with the shape of the measured curve.

3.2 CHANGE IN BANK WORTH WITH BURNUP

The change in the seven-rod bank worth with core burnup was calculated using the CANDLER-2 code for the IBM-704 computer. These calculations were compared to measured data at 0 MWYR and are shown in Fig. 3.2. There is a small but definite increase in the calculated rod worth near the top of the core with core burnup. This trend can also be seen in similar calculations performed on the SM-1 Core I, where both the calculated and the measured data show an increase in control rod worth near the top of the core. Unfortunately, limitations on both the calculational and measured techniques do not permit a traverse over the entire core height.

An uncertainty exists in the analytical model which is of some concern. Since the homogeneous thermal absorption cross-section, which simulates the control rod bank, is held constant with core burnup, the calculated rod worth would be expected to increase for that reason alone. The relative worth of the rods would increase since the absorption in the rest of the core decreases due to fuel and boron depletion.

Although agreement with measurements using this model is reasonably good, the question of whether the rod absorption cross-section decreases, increases, or remains constant with core burnup still remains unanswered.

3.3 INITIAL SEVEN-ROD BANK POSITIONS

The seven-rod bank position for the SM-2 experimental core at 68° F was calculated by WINDOWSHADE,⁽¹⁰⁾ using the best estimate of the material content and the revised MUFT-III cross-section files, and compared to the measured bank position. In addition, seven-rod bank positions were obtained for the SM-2 reference core at 0 MWYR in the cold, clean (68°F), hot, clean (510°F), and hot, equilibrium xenon operating conditions. (See Table 3.1). Agreement is very good in the experimental core, which lends reliability to the predicted reference core bank positions.

TABLE 3.1
INITIAL SEVEN-ROD BANK POSITIONS FOR SM-2

<u>Core and Operating Condition</u>	<u>Seven-Rod Bank Position - Inches from Bottom of Core</u>		
	<u>Measured</u>	<u>Calculated</u>	<u>Difference Calculated-Measured</u>
Exp. Core - 68°F	7.14	7.36	0.22
Ref. Core - 68°F	-	6.85	-
Ref. Core - 510°F Clean	-	12.0	-
Ref. Core - 510°F Eq. Xenon	-	14.2	-

3.1 Integral Seven-Rod Bank Worth in the SM-2 Experimental Core at 68° F.

3.2 Calibration of Seven-Rod Bank in SM-2 Core at 510° F During Life of Core.

4.0 REFLECTOR AND INTEGRAL FLUX SUPPRESSORS

Using the revised SM-2 files, calculations were made of the reactivity worth of the stainless steel reflector in SM-2. The effect of decreasing the power spike at the edge of the core was also investigated. In addition, the reactivity and power distribution effects of the integral europium oxide flux suppressors at the bottom of the fixed fuel element plates were examined.

4.1 EFFECT OF THICKNESS OF LAMINATED RADIAL REFLECTOR

Measurements were made in APAE No. 54 ⁽¹¹⁾ on the reactivity effect of placing stainless steel slabs against the edges of the SM-2 experimental core. First, a 1/2-in. slab to mock up the stainless steel skirt was installed, then 1-in. slabs spaced by 1/4-in. of water. These measurements showed an initial loss in reactivity for the first 1/2-in. slab which was quickly regained by the addition of the next 1-in. slab. Each additional steel slab showed a further increase in reactivity. (See Fig. 4.1.)

The calculations of this array using VALPROD ⁽¹²⁾ and the revised Alco stainless steel files showed a similar shape curve except that the steel reflector was always worth less than the water reflector by about 0.5% ρ even for a large steel reflector. Measurements indicated that a large steel reflector would be worth about 0.6% ρ more than a water reflector.

The reason that steel is eventually worth more than water as a reflector lies in the scattering of fast neutrons back into the core. Steel is a much larger absorber of thermal neutrons than water, as can be seen by the eliminations of the power spike which is caused by the thermal neutron flux, at the core reflector interface. (See Fig. 4.2.) This gives the initial reactivity decrease for thin steel reflectors; however, for larger steel thicknesses, the scattering of fast neutrons back into the core becomes the dominant effect. Water, on the other hand, thermalizes the fast neutrons and scatters back mainly thermal neutrons.

Thermal neutrons are worth less than fast neutrons since they do not diffuse as far back toward the center of the core which makes water a comparatively poor reflector material. This has been shown in previous Alco reports. (11), (3).

The Alco steel files show apparently poor agreement with the measured data; however, only small changes in the file are necessary to adjust to the measured reactivity value of the stainless steel reflector, since the reactivity effect is very sensitive to the fast microscopic absorption cross-sections used in the MUFT-III file. At the same time, a small change in these cross-sections would have only minor effects upon the core parameters or core reactivity.

In order to verify this, the steel files used in the reflector were replaced by the MUFT-V files obtained from Phillips.⁽⁷⁾ Absorption cross-sections in this file are much smaller. This reactivity effect can be seen in Fig. 4.1. Apparently, the correct absorption cross-sections are somewhere between Alco's and Phillips' MUFT files.

4.2 EFFECT OF CORE BURNUP UPON WORTH OF LAMINATED REFLECTOR

Measurements of the stainless steel reflector worth as a function of core burnup were made on the SM-2 midlife mockup core. As seen in Fig. 4.3, the steel reflector has decreased in reactivity worth with core burnup. The calculations again show the same shape curve but much less worth for the steel reflector. Also, the calculations show almost no change in reflector worth with core burnup.

4.3 INTEGRAL FLUX SUPPRESSORS

The reactivity effect of the integral europium oxide flux suppressors at the bottom of the fixed element fuel plates was calculated as well as their effect upon the power spike at the bottom of the core. It is shown in Fig. 4.2 that the stainless steel reflector completely eliminates the radial power peak at the edge of the core. Figure 4.4 shows that the flux suppressors have completely eliminated the power spike at the bottom of the core. The nuclear constants used for calculating the flux suppressor region at 68° F and at 510° F are listed in Table 2.6.

The reactivity effect of the flux suppressors was measured in APAE No. 54 Supplement I ⁽²⁾ as $-1.83\% \rho$ with the rod bank about 8 in. out. The calculated value is $2.2\% \rho$. Calculations of the SM-2 reference core with the rods out of the core show a smaller reactivity loss, $-0.44\% \rho$. However, this increases to $-0.90\% \rho$ at the operating temperature of 510° F.

4.1 Laminated Steel Reflector Reactivity Worth vs. Thickness of Steel for the SM-2 Experimental Core at 68° F.

4.2 Power Spike at Edge of SM-2 Reference Core at 68° F vs. Thickness of Steel Reflector

4.3 Laminated Steel Reflector Worth vs. Steel Thickness for the SM-2 Midlife Mockup Core at 68° F.

4.4 Axial Power Distribution in the SM-2 Experimental Core at 68° F with and without Flux Suppressors.

5.0 POWER DISTRIBUTIONS

Power distributions for the SM-2 experimental core were calculated using the PDQ, IBM-704 code ⁽¹³⁾ in x, y geometry and the WINDOWSHADE and VALPROD ⁽¹²⁾ IBM-650 codes for the axial distribution. Separability of the power distribution into radial and axial components was assumed, i.e., $P(x, y) P(z) = P(x, y, z)$.

5.1 GROSS AND LOCAL POWER DISTRIBUTIONS

Table 5.1 shows the power generation in each fuel element normalized to a core average of unity. Discrepancy between calculated and measured data is $\pm 8\%$ which is of the order of the reported experimental error ($\pm 5\%$). Most of the calculated element averages are greater than the measured values. Power values at the center of each element are listed in Table 5.2. Again, the calculated values consistently overestimate the measured values by 7 to 15%. In this case, however, the error may be attributed to the calculated axial power distribution, $P(z)$. As shown in APAE Memo No. 286 ⁽³⁾ the experimental data, when normalized to the calculated $P(x, y)$ value at the center of the core to eliminate dependence on the axial power distribution, shows excellent agreement with the calculated data at the center of the elements. Curves of the axial power distribution, using the best calculational technique available, show that the calculated values are greater by about 10%. Correcting for the axial difference, all the values are within $\pm 4\%$.

Calculated corner power peaking in the elements usually is underestimated by about 15%; however, as seen in Table 5.3, the combination of the calculated radial corner peak and the calculated axial power peak gives a correction factor of about 1.0 for most elements. This agreement is fortuitous and results from an underestimation of the local corner peak and an overestimation of the axial peak.

TABLE 5.1
POWER GENERATION IN EACH SM-2 ELEMENT
FOR THE EXPERIMENTAL CORE - 68°F

<u>Element No.</u>	<u>Calculated PDQ (x, y) Axial Power Weighted</u>	<u>Measured APAE No. 54 Suppl. 1</u>	<u>F correction (meas./calc.)</u>
45	1.377	1.353	0.98
46	1.146	1.187	1.04
47	0.829	0.818	0.99
54	1.389	1.423	1.02
55	1.324	1.278	0.97
57	0.755	0.728	0.96
65	1.178	1.193	1.01
66	0.971	0.965	0.99
67	0.631	0.581	0.92
74	0.894	0.839	0.94
75	0.876	0.812	0.93
76	0.688	0.645	0.94
C.R. Fuel El. A 64	0.595	0.547	0.92
C.R. Fuel El. C 44	0.763	0.679	0.89
C.R. Fuel El. F 56	0.553	0.509	0.92

Note: Power normalized to core average of unity.

TABLE 5.2

CALCULATED AND MEASURED POWER DATA AT THE
CENTER OF THE ELEMENTS IN THE SM-2 EXPERIMENTAL
CORE - 68° F.

Element No.		Center Power (5 in. Axial Plane)		F correction (Meas./Calc.)
Quad. 4	Quad. 1	Measured P(x, y, z)	Calculated P(x, y) P(z)	
44	44	2.43	2.60	0.93
45	43	2.24	2.51	0.89
46	42	1.83	2.04	0.90
47	41	1.15	1.32	0.87
54	34	2.20	2.51	0.88
55	33	2.11	2.35	0.90
57	31	1.18	1.35	0.87
65	23	1.78	1.93	0.92
66	22	1.43	1.55	0.92
67	21	0.95	1.06	0.90
74	14	1.28	1.37	0.93
75	13	1.15	1.35	0.85
76	12	0.90	1.06	0.85

TABLE 5.3

CALCULATED AND MEASURED POWER PEAKING IN THE
SM-2 EXPERIMENTAL CORE - 68° F

Quad. 4	Element No.	Quad. 1	Power Peak (5 in. Axial Plane Corner)		F Correction (Meas./Calc.)
			Measured	Calculated	
44		44	4.39	4.13	1.06
45		43	4.21*	4.08	1.03
46		42	4.07	3.82	1.07
47		41	2.63*	2.64	1.00
54		34	4.32	4.35	0.99
55		33	4.04	4.04	1.00
57		31	2.65	2.64	1.00
65		23	3.76	3.55	1.06
66		22	3.45	3.36	1.03
67		21	2.20*	2.29	0.96
74		14	2.92	2.89	1.01
75		13	2.87	2.66	1.08
76		12	2.36	2.24	1.05

* Peak does not occur in corner.

5.2 EFFECT OF FLOW DIVIDER

Measurements were made in APAE No. 54, Supplement I ⁽²⁾ on the flow divider reactivity worth for two cases: a gap containing a steel flow divider and water, and a gap containing only water. The measured data showed a loss in reactivity of $0.22\% \rho$ for the water gap and a 0.86% loss for the steel-water gap. Calculations showed a gain in reactivity of $0.32\% \rho$ for the water gap, and a 0.79% loss in reactivity for the steel-water gap. The agreement obtained in the steel-water gap is excellent. While the change in reactivity with an all-water gap is small, there is disagreement as to whether the change is positive or negative.

5.3 EFFECT OF FLOW DIVIDER UPON POWER PEAKING FACTORS

A revised mockup of the SM-2 experimental core at 68° F was analyzed for the change in power peaking when the flow divider was present. Tables 5.4 and 5.5 list the maximum calculated and measured local power peaking in the fuel elements adjacent to the flow divider. In Table 5.4, the flow divider is present while in Table 5.5 the fuel elements are spaced normally, as with no flow divider.

When the flow divider is included, both measured and calculated data show some definite decreases in power peaking, contrary to expectation. The decrease is partly because the rods were about 1-in. further out of the core due to the negative reactivity effect of the flow divider and flux suppressors. Another factor which kept the power peaking down was the stainless steel flow divider. The steel took up most of the gap between the elements. The total gap is 0.245 in. of which the steel is 0.125 in. This leaves only 60 mils of additional water on each side of the steel, which is relatively small, considering that the normal water gap between fuel plates is 123 mils.

5.4 REVIEW OF THE POWER DISTRIBUTION IN THE SM-2 REFERENCE CORE

The power distribution data presented in this report contains supplementary information to the data supplied in APAE Memo No. 286, ⁽³⁾ and in no way supersedes the final data in APAE Memo No. 286. The power distributions in the latter report are considered to be the best estimate for the SM-2 reference core.

TABLE 5.4 - LOCAL POWER PEAKING NEAR FLOW
DIVIDER IN REVISED SM-2 EXPERIMENTAL MOCKUP - 68° F

Element No.	Position		Measured P (x, y, z)	Calculated		F Total Correction
	Plate	Plane (WRP)		$\frac{P(x,y)}{P(z) = 1.80}$	$\frac{P(x,y)P(z)}{P(z) = 1.80}$	
12	a	4.75	2.02	1.07	1.93	1.05
13	a	4.33	2.26	1.20	2.16	1.05
	a	1.81	2.86	1.52	2.74	1.04
14	a	1.26	2.90	1.67	3.01	0.96
	a	C.R.P.	2.21	1.22	2.20	1.00
21	a	7.68	2.01	1.10	1.98	1.02
22	a	7.27	2.33	1.25	2.25	1.04
	a	4.75	3.16	1.66	2.99	1.06
	r	4.75	2.15	1.07	1.93	1.11
23	a	4.20	3.49	1.59	2.86	1.22
	r	4.20	2.26	1.22	2.20	1.03
	r	1.68	2.52	1.66	2.99	0.84
C.R.A.	p	1.16	2.98	1.60	2.88	1.03
	p	C.R.P.	2.03	1.28	2.30	0.88
31	a	10.20	1.39	0.74	1.33	1.05
	a	7.68	2.84	1.67	3.01	0.94
	r	7.68	2.24	1.10	1.98	1.13
C.R.F.	p	7.04	2.56	1.37	2.47	1.04
	p	4.72	3.42	1.76	3.17	1.08
	a	7.04	2.77	1.54	2.77	1.00
41	r	10.20	1.29	0.77	1.39	0.93
	r	7.68	2.43	1.71	3.08	0.79
42	r	7.14	2.86	1.62	2.92	0.98
	j	7.14	2.61	1.38	2.48	1.05

Note: Control rod element flux suppressors are present in the measured data.
Rod bank is one inch further out.

TABLE 5.5 LOCAL POWER PEAKING WITH NO FLOW
DIVIDER IN SM-2 EXP. CORE — 68° F.
THROUGH 5 IN. AXIAL PLANE

Element No.	Position		Measured P(x, y, z)	Calculated $\frac{P(x,y)}{P(z)} \frac{P(x,y)P(z)}{P(z) = 1.82}$		F Total Correc- tion
	Plate	Plane (WRP)				
12		4.62	2.36	1.23	2.24	1.05
13	a	4.20	2.23	1.26	2.29	0.97
	a	1.68	2.87	1.46	2.66	1.08
14	a	1.26	3.32	1.59	2.89	1.15
	a	C.R. P.	1.97	1.12	2.04	0.97
21	a	7.55	2.20	1.26	2.29	0.96
22	a	7.14	2.43	1.41	2.57	0.95
	a	4.62	3.45	1.85	3.37	1.02
	r	4.62	2.48	1.23	2.24	1.11
23	a	4.20	3.32	1.74	3.17	1.05
	r	4.20	2.36	1.26	2.29	1.03
	r	1.68	2.73	1.46	2.66	1.03
C.R. A.	p	1.16	2.84	1.53	2.78	1.02
	p	C.R. P.	2.04	1.13	2.06	0.99
31	a	10.07	1.24	0.66	1.20	1.03
	a	7.55	2.65	1.45	2.64	1.00
	r	7.55	2.17	1.26	2.29	0.95
C.R. F.	p	7.03	-	1.35	2.46	-
	p	4.73	3.00	1.75	3.19	0.94
	a	7.03	2.45	1.53	2.78	0.88
41	r	10.07	1.30	0.66	1.20	1.08
	r	7.55	2.31	1.45	2.64	0.88
42	r	7.14	3.00	1.61	2.93	1.02
	j	7.14	2.82	1.47	2.68	1.05

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6.0 MISCELLANEOUS CALCULATIONS

Additional calculations on the SM-2 core were performed on the temperature coefficient and pressure coefficient of reactivity and their comparison with measured results. The effect of the changes in boron loading upon core lifetime was also evaluated.

6.1 CORE LIFE OF THE SM-2 REFERENCE CORE

The burnup behavior of the SM-2 reference core is presented in AP Note 366 (4). In order to ensure a multiplication factor of 1.03 at startup in the hot (510° F), equilibrium xenon operating condition, small changes in the boron loading have been made as more experimental data has become available. These changes, however, will have no significant effect upon the core lifetime since the boron is 95% depleted near the end of core life.

6.2 TEMPERATURE COEFFICIENT AND DEFECT

6.2.1 Background

The present discussion summarizes the work on temperature coefficient and defect previously reported in APAE No. 69, Vol. III (1) and presents additional analysis performed since the issue of APAE No. 69.

6.2.2 SM-2 Results

Figure 6.1 presents the best estimate of temperature coefficient, α vs. temperature. α in $\text{¢}/^{\circ}\text{F}$ may be converted to α in $\text{‰}/^{\circ}\text{F}$ by using an effective delayed neutron fraction of 0.0078. SPERT III measured values (as given in IDO-16586 (14)) are included for comparison.

The calculated temperature defect, Δ , from 68° F at atmospheric pressure to 510° F at 2000 psi obtained from rod bank position and differential rod bank worth vs. position measurements is -769 ¢. This result is derived from experiments on the SM-2 reported in APAE No. 54, Supplement No.1. The analytically determined temperature defect for the reference core is 5.91%₀ or 780¢ *

* See Table 2.1

6.2.3 Discussion of Results

The experimental temperature coefficients from 68 to 155° F were obtained by uniform heating of the SM-2 mockup coolant (moderator) and reflector with immersion heaters. Temperature coefficients from 165° F to 510° F were obtained by inserting aluminum strips into the coolant channels to simulate the reduced water density, at 2000 psi. The detailed experimental technique employed is presented in APAE No. 54;⁽¹¹⁾ justification for the use of the aluminum heating method is discussed in Vol. III of APAE No. 69.⁽¹⁾

Temperature coefficients from the aluminum heating data were obtained by calibrating the seven-control rod bank as a function of position. From this calibration, a curve of integral bank worth, $\rho_1(x) = \int_0^x \frac{\partial \rho}{\partial x} dx$, vs. seven-rod bank, position was obtained. The bank position required to maintain criticality at a given simulated temperature was converted to an integrated worth by using this curve, and a plot of integral worth vs. simulated temperature made.

This curve was normalized to the heating value of ΔK obtained at 103° F. The resulting curve is presented in Fig. 6.2. A least squares fourth degree polynomial fit was made to this curve. The derivative of this polynomial with respect to temperature yielded an equation for the temperature coefficient vs. temperature.

Since reduced water density was simulated with aluminum in the stationary and control rod fuel elements and not in the reflector or control rod absorber sections for all experimentally simulated temperatures except 510° F, the effect of a cold reflector on the temperature coefficient was investigated. Experiment yielded a core reactivity increase of approximately 16.8 ¢ in going from a hot core (510° F), a cold reflector (68° F), cold control rod absorber sections, to a hot core, hot (510° F) reflector, and hot control rod absorber sections. Analytical calculations yielded a core reactivity increase of 34 ¢ for a change in reflector temperature from 68° F to 510° F for a core temperature fixed at 510° F. For the core at 440° F, the analytically determined increase in reactivity for a reflector temperature change from 68° to 440° F was 29 ¢. These values are shown plotted in Fig. 6.3. To determine the effect of reflector and control rod absorber temperature on measured core temperature coefficient, the integral worth data, discussed previously and presented in Fig. 6.2, was corrected using the experimental curve of Fig. 6.3. Again, a least squares fourth degree polynomial fit was made and differentiated to obtain an expression for the temperature coefficient. The results are summarized in Table 6.1.

6.1 Temperature Coefficient vs. Temperature

6.2 Reactivity of SM-2 Mockup vs. Temperature at 2000 psi.

TABLE 6.1

TEMPERATURE COEFFICIENTS FOR
VARIOUS REFLECTOR TEMPERATURES

<u>Core Temperature</u>	<u>Temperature Coefficient with Reflector at 68°F.</u>	<u>Temperature Coefficient with Reflector at Core Temperature</u>
°F	¢/°F	¢/°F
510	4.38	4.34
400	3.02	2.90
300	2.07	2.03
200	1.32	1.28
100	0.67	0.64

Reflector temperature changes affect the temperature coefficient by less than 5%.

The SM-2 temperature coefficient curve of Fig. 6.1 was obtained from the data of Table 6.1, column 3, by normalizing the curve of the bulk coefficient of expansion of water at constant pressure (2000 psi) to the average value of the

ratio, $\alpha_i \frac{1}{D_i} \frac{\partial D_i}{\partial T_i}$, where α_i ($i = 1$ to 5) is given in Table 6.1, and $\frac{1}{D_i} \frac{\partial D_i}{\partial T_i}$ is

the bulk coefficient of expansion of water at the temperature corresponding to the temperature at which α_i was calculated. This normalization was performed in order to extrapolate the temperature coefficient curve beyond 510°F. The resulting equation is:

$$\alpha (\text{¢/°F}) = 3580 \left[\frac{1}{D} \frac{\partial D}{\partial T} \right]_{P = 2000 \text{ psi}}$$

The values of α calculated using the above equation in the range of 100 to 510°F agree quite well with the values of α given by Fig. 7.1 of APAE No. 69, Vol. III⁽¹⁾ (i.e., obtained directly from graphical estimation of the slope of the integral worth vs. temperature curve, Fig. 6.2 of this report, which was not corrected for reflector temperature and not normalized to the bulk coefficient of expansion of water). Also, the Δ obtained by integrating the curve of Fig. 6.1 from 70 to 510°F agrees to within 7% of the Δ obtained from rod bank position and differential rod bank worth vs. position measurements.

6.3 PRESSURE COEFFICIENT

The pressure coefficient of reactivity was calculated from:

$$\frac{\partial \rho}{\partial P} = \left(\frac{\partial \rho}{\partial T} \right)_P \left(\frac{\partial T}{\partial P} \right)_D,$$

where

T = reactor moderator temperature

D = the density of water

P = reactor pressure

$$\left(\frac{\partial \rho}{\partial T} \right)_P = \text{temperature coefficient.}$$

As with the temperature coefficient evaluation, it was assumed that the change in reactivity brought about by a variation in pressure was due solely to the corresponding change in water density.

The curve of Fig. 6.4 was obtained using values of $\left(\frac{\partial \rho}{\partial T} \right)_P$ from Fig. 6.1; the values of $\left(\frac{\partial T}{\partial P} \right)_D$ were calculated from data given in standard tables. (15)

6.3 Reactivity Change vs. Core Temperature

6.4 SM-2 Pressure Coefficient vs. Temperature

7.0 REACTIVITY AND BANK POSITIONS OF SM-2 REFERENCE CORE

7.1 INTRODUCTION

Previous work reported in APAE No. 69⁽¹⁾ has shown that a U-235 loading of 46.30 gm/plate* in 684 fixed fuel element plates and 40.98 gm/plate in 112 control rod fuel element plates was sufficient to meet the lifetime requirements for the SM-2. The total poison loading was also calculated to be 56.8 gm of B-10. Since the work in APAE No. 69 was completed, however, additional experimental information has become available⁽²⁾ and enables a redetermination of the poison loading. A discussion of the procedure used to calculate this poison loading follows.

The optimum poison loading of the reference SM-2 is defined as that loading which will result in a K_{eff} of 1.030 at 0 MWYR, operating conditions (510°F and 2000 psi), with equilibrium xenon, with all rods out, and represents a compromise between the need for adequate startup and shutdown margins. To obtain the B-10 loading of the reference SM-2, a mockup was assembled, and a B-10 loading of the mockup which would result in a mockup K_{eff} of 1.030 was calculated. After adjustment, this loading is taken to be the B-10 loading of the reference SM-2.

In order to provide flexibility of B-10 loadings in the mockup, it was decided that the mockup fuel plates would be manufactured with no boron and that boron loadings would be simulated by applying boron impregnated Mylar tape to the outside of the mockup fuel plates. Also, since there was a large uncertainty (at the time of manufacture of the mockup plates) in the boron loss occurring during fabrication of fuel plates containing boron, it was felt that the total quantity of boron loaded into the mockup could be determined more accurately by the use of these boron impregnated tapes.

In this, and several other ways the mockup differed from the reference SM-2. These differences are listed in Table 7.1.

* All material quantities reported in this section are "as loaded" quantities and not effective nuclear loadings.

TABLE 7.1

REFERENCE & MOCK-UP CORE DIFFERENCES

	<u>Reference SM-2</u>	<u>SM-2 Mockup</u>
1. B-10 poison	Homogeneous with meat as ZrB_2	On surface of fuel plate as Mylar tape and B_4C .
2. Operating condition	2000 psi, 510°F	2000 psi at 510°F simulated by addition of Al strips into coolant channels
3. Flux suppressors	Eu_2O_3	None
4. Xenon	Equilibrium	None
5. Side plate thickness	0.040 in.	0.0327 in.
6. Meat length	22.0 in. *	21.6 in. *
7. Meat width	2.65 in.	2.51 in.
8. Plate width	2.84 in.	2.77 in.
9. Boron condition	100 micron ZrB_2	1 micron B_4C
10. Uranium oxide	112 micron spherical	66 micron Geneva
11. Plate reduction in rolling	6 to 1	14 to 1

7.2 DETERMINATION OF FUEL PLATE LOADINGS7.2.1 U-235 Loading

The values of 46.3 gm/plate in the fixed fuel element plates and 40.98 gm/plate in the control rod fuel element plates, as calculated in APAE No. 69, Vol. III, ⁽¹⁾ are taken to be fuel loadings of the reference SM-2.

* Although meat dimensions are slightly different, the total weight of U-235 in an average mockup plate and a reference core fuel plate, is the same.

7.2.2 Boron-10 Loading

One of the major problems in assembling the mockup was the determination of the amount of B-10 loaded. Chemical analyses for B-10 content were performed on representative samples from two separate orders of Mylar tape. The results, (2) as reported independently by two laboratories, are given in Table 7.2.

TABLE 7.2
B-10 CONTENT OF MYLAR TAPE

<u>Method of Determination</u>	<u>B-10 Content mg/cm²</u>	
	<u>Batch #1 Tape</u>	<u>Batch #2 Tape</u>
Chemical, Lab #1	0.1717	0.0709
Chemical, Lab #1	0.1591	0.0574
Chemical, Lab #2	0.1408	0.0551
Chemical, Lab #2	0.1417	0.0559
Reactivity measurements, Alco	0.1578 +	0.0752 ++

+ Average of 3 measurements.

++ Average of 9 measurements.

As may be seen from this table, the results reported by Lab #1 do not agree among themselves, and although the results of Lab #2 agree among themselves, they are not consistent with the results of Lab #1. The results of neither Lab agrees with the results obtained by reactivity measurements at Alco. *

The sensitivity of the reactivity measurements is such that a change in B-10 content of approximately $\pm 7\%$ (at 0.070 mg/cm^2) is detectable. The absolute average deviation in the measured (by reactivity) B-10 content of Batch #2 tapes is only approximately $\pm 1.5\%$. Thus, the actual difference in B-10 content of portions of tape from the same batch is not measurable using the reactivity technique and is less than $\pm 7\%$ for tapes containing a nominal loading of 0.070 mg/cm^2 . On the basis of the above conclusion, the results of the chemical analyses of Lab #1 may be rejected since they indicate a B-10 variation within the same batch of tape of approximately $\pm 10.5\%$.

The difference in B-10 content of tapes as determined in Lab #2 and by reactivity measurements is unresolved.

* Details of the reactivity procedure are given in APAE No. 54, Supplement No. 1(2).

Since the reactivity experiments were performed under the direct control of Alco and since the reactivity measurements are known to be reproducible, it was decided to accept the B-10 loading of the tapes as determined by reactivity measurements in determining the total B-10 loading of the mockup. However, the uncertainty as to which tape loading is correct (if either is correct) still exists.

In an attempt to determine the equivalence of B-10 placed on the outside of a fuel plate to B-10 mixed homogeneously with fuel in the plate meat, the following experiment was performed. Two tapes of known B-10 content (as determined from reactivity measurements) were placed on a mockup fuel plate (containing no boron); this plate was designated the "standard plate". Seventeen other mockup plates which also had two boron containing tapes attached were calibrated by reactivity comparisons with this standard. All reactivity differences between the seventeen plates and the standard plate were assumed to be due to differences in the B-10 content of the attached tapes. In this manner the B-10 content of each of the seventeen plates was determined. The average of these 18 measurements was taken to be the B-10 loading per plate of the mockup. These 18 plates were then assembled into an element. The change in reactivity between this element and an element composed of 18 fuel plates manufactured by BMI, which are assumed identical to the reference SM-2 plates except for Eu_2O_3 flux suppressors at one end (BMI plates did not have flux suppressors), was converted to an equivalent amount of B-10. It was assumed that by adding this equivalent amount of B-10 uniformly to the 18 mockup plates, the reactivity worth of the mockup element would be identical to the BMI element. The experimental quantities are:

Average loading of 0.0974 gm/plate of B-10 on 18 mockup fuel plates, as Mylar tape yields the same reactivity worth per element as 0.0911 gm/plate* homogeneously incorporated into 18 BMI fuel plates.

It should be noted that this equivalence between B-10 on the surface and B-10 homogeneous is true only for the actual B-10 loading used in the experiment and is only approximately true in a small neighborhood about the experimental loading. Also this equivalence includes the effect of differences (other than the quantity and manner in which B-10 is present) between the mockup plates and the BMI plates. The known differences (from Table 7.1) are plate dimensions, boron condition, and fuel particle size.

* Determined by BMI by chemical analysis of rejected fuel plates.

As described previously in Section 7.1, the B-10 loading of the reference SM-2 was derived by altering the reference SM-2 core (i.e. removing the items listed in Table 7.1 which were not present in the mockup) to agree with the mockup and then calculating the B-10 loading required to yield a mockup K_{eff} of 1.030. The B-10 loading of the reference core was then obtained by converting the mockup B-10 loading to the reference core loading using the equivalence between B-10 on the surface and B-10 homogeneous with meat described above. This calculation proceeds as follows:

1. Begin with reference SM-2 core at 510°F, 2000 psi, with flux suppressors (at bottom of the fixed elements), with laminated stainless steel reflector, with design side plate thickness, with equilibrium Xe, with stainless steel flow divider and with B-10 homogeneously mixed with meat. K_{eff} with all rods out is 1.030 by definition, and the excess reactivity, ρ_{ex} , is 2.91% ρ .

2. Remove the flux suppressors. For the rods-out case, the analytically determined worth of the Eu_2O_3 suppressors at the bottom of the fixed fuel element plates is 0.90% at 510°F. * Therefore, the reference core without flux suppressors with rods out has an excess reactivity of 3.81% ρ .

3. Remove equilibrium xenon. The calculated worth of equilibrium xenon is 2.79% ρ . ** The reference core now has an excess reactivity of 6.60% ρ .

4. Decrease the side plate thickness from 0.040 in. to 0.0327 in. The analytically determined reactivity change is 0.27% ρ (APAE No. 69, Vol. III⁽¹⁾). The experimentally determined reactivity change for 38 fixed elements at 68°F is 0.18% ρ , per APAE No. 54, Supplement 1. ⁽²⁾ For 45 elements at 68°F the adjusted experimental reactivity change is 0.18% ρ $\left(\frac{0.540 \text{ kgm}}{4.72 \text{ kgm}}\right)$ *** + 0.18% ρ = 0.21% ρ . Using the analytically determined value of reactivity change, the core has an excess reactivity of 6.87% ρ or 915¢.

* See Section 4.3.

** See Section 7.4.

*** Ratio of the weights of stainless steel removed from side plates of 38 fixed elements to weight removed from 7 control rod elements.

5. Change the meat width from 2.65 in. to 2.51 in. Change plate width from 2.839 in. to 2.77 in. Change the meat length from 20.0 in. to 20.6 in. Change poison loading from x gm B-10 (as ZrB_2) in fuel plates to y gm B-10 (as B_4C on Mylar tape) on the surface of the plates. Based on critical experiment results, there will be no reactivity change due to these changes if $x = 0.935 y$. * Therefore the excess reactivity is 915¢.

6. Adjust the boron loading by adding z gm of B-10 (as Mylar tape). Since the average worth of B-10 from experiment is 34.9¢/gm at 510°F (APAE No. 54, Supplement No. 1⁽²⁾), the excess reactivity of the core is now $915 - 34.9 z$ and the poison loading is $y + z$ gm of B-10 (Mylar tape).

By integrating the experimentally determined differential rod worth vs. rod position curve, this core (experimental core) has an excess reactivity (APAE No. 54, Supplement 1⁽²⁾, Fig. 4.6) of 527¢ and a B-10 loading (determined by reactivity measurements) of 67.9 gm. Thus:

$$915 - 34.9 z = 527$$

$$y + z = 67.9$$

$$x = 0.935 y,$$

$$\text{and } x = 53.1 \text{ gm of B-10.}$$

The total, actual B-10 loading of the reference core must therefore be 53.1 gm or 62.4 mg per fixed fuel element plate and 62.7 mg per control rod fuel element plate, for a K_{eff} of 1.030 at operating conditions with equilibrium xenon and at 0 MWYR.

7.2.3 Comparison with Previously Calculated B-10 Loadings

The present analysis differs in several respects from the analysis presented in APAE No. 69, Vol. III.⁽¹⁾ There the B-10 loading was calculated to be 56.8 gm and is based only on part of the results of APAE No. 54, Supplement 1.⁽²⁾ The differences between the two analyses are presented in Table 7.3.

* The factor 0.935 is obtained from the equivalence stated previously, that 0.0974 gm of B-10 on the mockup fuel plate as Mylar tape is equivalent to 0.0911 gm of B-10 homogeneously incorporated into a BMI fuel plate.

TABLE 7.3

DIFFERENCES BETWEEN PRESENT AND PREVIOUS
DETERMINATION OF B-10 LOADING

<u>Item</u>	<u>APAE 69</u>	<u>Present Work</u>
1. Flux Suppressors	0.83% ρ	.90% ρ
2. Flow Divider	0.97% ρ	1.10% ρ *
3. Cooling & Depressurizing	6.63% ρ	5.8% ρ *
4. Water to SS Reflector	0.67% ρ	unknown *
5. Mockup excess reactivity	1520¢ ⁺	527¢ ⁺⁺
6. Core average B-10 Worth	42.5¢/gm ⁺	34.9¢/gm ⁺⁺

+ Determined experimentally at 68°F.

++ Determined experimentally at simulated temperature and pressure of 510°F and 2000 psi.

7.3 DISCUSSION OF RESULTS

The value of 53.1 gm of B-10 obtained as the loading of the SM-2 rests on two primary assumptions, the validity of which are difficult to access without additional experimental and analytical work. The first of these concerns the boron content of the Mylar tape. Until the discrepancies that exist between chemical analysis and the reactivity determination are resolved, only limited confidence can be placed in the value obtained by reactivity measurements. Neutron transmission measurements on the tapes could be invoked as a third (and independent) method of determining the tape loadings and uniformity of loading.

* These values are not presented explicitly in the preceding calculation of B-10 loading but are included in the value of 527¢ which was obtained by integrating the experimentally obtained differential rod worth vs. rod position curve of APAE No. 54, Supplement 1.

The second assumption concerns the self-shielding factors for the boron on the surface of the fuel plate in the tape, g_e , and the boron mixed homogeneously with meat, g_h . If the actual B-10 content of the tape is y gm and the B-10 content of the meat is x gm, then for fuel plates which are the same except for the amount and distribution of B-10, and which have equal reactivity worth, $xg_h = yg_e$. Since x and y were assumed known, the ratio of self-shielding factors ($g_e/g_h = .935$) could be obtained for one B-10 concentration in tape and meat (i. e. 0.0974 gm/plate B-10 as Mylar tape is equivalent to 0.0911 gm/plate homogeneously mixed with meat). The error involved in assuming that g_e/g_h is independent of temperature and the value of x and y , is not known and is difficult to calculate. In the preceding analysis g_e/g_h was assumed independent of temperature from 68°F (the temperature of the experiment) to 510°F (the temperature at which g_e/g_h was invoked) and independent of B-10 loading from 0.0911 gm/plate to 0.0674 gm/plate, a decrease in B-10 loading of 26%.

One would expect that there would be more self-shielding for B-10 in the plate than on the surface, and thus $g_e/g_h > 1$. This expectation was verified by computations with the Tranvar Code. Thus, there is evidence that the value of y (and possibly also x *) used to obtain 0.935 is in error. This discrepancy might disappear if more accurate values of the B-10 content in the tape and meat are obtained.

It can be shown that if only one batch of tape had been used, and if the B-10 were distributed uniformly along the length of the entire batch, then the calculated value of the B-10 loading of the reference SM-2 is only an implicit function of the tape loading (i. e. depends on tape loading only through ρ excess, reactivity changes, etc., measured in the experimental core).

Since, however, two batches of tapes with different B-10 loadings were actually used in the experiment (see Table 7.2), the calculated value of the reference core loading does depend slightly on the value chosen for the tape loading. For example, the B-10 loading of the reference core was calculated from experimental data based on the value of the Mylar tape loadings as determined by chemical analysis performed by Lab. #2. The resulting reference core B-10 loading is 55.9 gm. In this calculation the total experimental core B-10 loading, based on chemistry of Mylar tape by Lab. #2, differed from the B-10 loading of the same core, based on reactivity determination of B-10 in Mylar, by 16.3%**; however, the difference in the calculated reference loading is only 5%.

* The value of x (.0911 gm of B-10/plate) was obtained from chemical analysis performed by BMI on rejected fuel plates.

** Physically, of course, the quantity of B-10 in the experimental core did not change; only the estimation of this quantity changed.

From the reasons stated previously, the B-10 content of the Mylar tape as determined by Alco reactivity measurements is taken to be the basis for determining the loading of the experimental core. Based on this number, the B-10 loading of the reference core is 53.1 gm.

7.4 SUMMARY OF SM-2 REACTIVITY

The initial reactivity of the SM-2 core under various conditions is shown in Table 7.4. Burnout calculations indicate that maximum core reactivity occurs at 12 MWYR. Reactivity values are also given for this burnup. The reactivity values shown in the table are based on the following assumptions:

1. The core, as manufactured, is loaded such that the initial $K_{\text{eff}} = 1.030$ at 510°F, with equilibrium xenon.
2. The following reactivity values apply:
 - a. Equilibrium Xe = $-2.8\% \rho$
 - b. Peak Xe = $-1.2\% \rho$
 - c. Hot to cold change = $5.9\% \rho$
 - d. Core burnups 0 to 12 MWYR = $4.4\% \rho$
3. All reactivity effects are additive.

TABLE 7.4
SM-2 CORE REACTIVITY

<u>Core Condition</u>	<u>Core Reactivity at 0 MWYR</u>	<u>Core Reactivity at 12 MWYR</u>
1. 69°F, no Xe,	11.6% ρ	16.0% ρ
2. 510°F, no Xe,	5.7% ρ	10.1% ρ
3. 510°F, eq. Xe,	2.9% ρ	7.6% ρ
4. 510°F, pk. Xe,	1.7% ρ	5.9% ρ

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8.0 CONCLUSIONS AND RECOMMENDATIONS

A review of the analytical models was made to determine which model best predicts experimental measured data of core excess reactivities, percent of fissions which are thermal, and power distributions. Modified two-group theory was employed with thermal parameters calculated by P₃ theory using thermal cross sections averaged over a hardened Maxwell-Boltzmann distribution. For the fast parameters at the beginning of core life, Alco's MUFT-III files were compared for both P-1 and P-1 SG slowing down approximations. The best agreement with measured values was obtained by use of Alco's MUFT-III files using the P-1 slowing down approximation. It was found that the calculated reactivity of the experimental core underestimates the measured value by about 0.6% ρ . Similar work performed under Task 2.3 of the Army PWR Research and Development Program showed that the predicted reactivities of various SM-1 cores in general underestimate the measured values by about 0.5% ρ . Therefore, predictions of cold excess reactivities of the SM-2 reference core should be accurate to about $\pm 1.0\% \rho$.

Unfortunately, the CANDLE code, which was used to predict reactivity variation during core burnup, calculates the nuclear parameters in a different manner than the techniques described above. In addition, the cold core reactivity variation with fuel burnup was not calculated; the cold-to-hot reactivity change at 0 MWYR was assumed to remain constant during core life. Measurements made upon the SM-1 Core I showed that the temperature defect remained constant, within the limits of experimental error; however, one cannot assume this to be true for the SM-2 core without further investigation.

The calculations of the integral seven rod bank worth vs. bank position at 0 MWYR, 68°F, using axial VALPROD with the rods represented by a constant homogeneous poison, Σ_p used in these calculations was assumed to remain constant both with bank position and as a function of core life. The validity of this assumption would require further investigation. The maximum reactivity to be controlled (at midlife) is expected to be $18.3 \pm 1.0\% \rho$, resulting in a safety margin of 4.5% ρ with rods inserted. Measurements made upon a midlife mockup of the SM-2 core ⁽¹¹⁾ indicate no control problems for the core in the most reactive condition.

Both calculations and measurements verify the effectiveness of the laminated steel radial reflector and of the integral flux suppressors in reducing power peaking at the outside edges and bottoms of the core, respectively. The flux suppressors reduce core reactivity by a value which is a function of the bank position, whereas the use of a thick laminated reflector tends to increase core reactivity.

Calculations and measurements show that the use of a flow divider tends to decrease the local power peaking in the fuel elements. Therefore, the power

peaking factors for the SM-2 reference core, as reported in APAE Memo 286 (3), may be considered conservative for thermal calculations.

The calculated core life of the SM-2 by the CANDLE code is 29.6 MWYR. Based upon similar calculations on the SM-1 Core I, a lifetime of 16.9 MWYR is predicted as compared to a measured value of 16.4 MWYR; therefore, the minimum lifetime of the reference SM-2 core may be considered to be 28.7 MWYR.

The temperature coefficient was measured in the SM-2 mockup experiments by the addition of aluminum to the core to simulate the density change of water with temperature. Measurements performed upon the SM-1 Core I indicate that within the limits of experimental error, the aluminum measurements give a good approximation of the heating data, especially for the higher core temperatures. The best estimates of the temperature coefficient for the reference SM-2 core are $-0.35 \times 10^{-4} \Delta K/^{\circ}F$ and $-3.3 \times 10^{-4} \Delta K/^{\circ}F$ at $68^{\circ}F$ and $510^{\circ}F$, respectively.

One of the most difficult parameters to specify is the reference B-10 loading for the SM-2 core. Two approaches are possible:

- a. Calculate the reactivity of the reference core as a function of B-10 loading, by the best available analytical models, to ascertain the loading necessary to yield a K_{eff} of 1.03 at $510^{\circ}F$, with equilibrium xenon.
- b. Relate the experimental core mockup to the reference core, adjusting the measured reactivity of the former core to compensate for all differences in geometry and other parameters, and finally determining the B-10 loading necessary to yield the desired reactivity of the reference core.

The first approach is purely analytical and is subject to all errors inherent in the calculational models. The second approach uses a combination of analytical predictions and measured reactivity effects, wherever possible. The first approach was used for survey calculations in the early stages of the SM-2 project to determine tentative B-10 loadings. The second approach was used in this report to determine the final B-10 loading. The largest sources of error in the second approach are in the relation between boron on the surface of the fuel plates vs. boron in the fuel matrix and in the determination of the Mylar tape loading. The best estimates for the final loadings for the reference SM-2 core are 36.3 kg and 53.1 gm for U-235 and B-10, respectively. The loadings and geometry for the core are described in detail in Section 7.0.

The preceding paragraphs summarize some of the difficulties encountered in fully analyzing a reactor core; the problems are not unique to any particular reactor systems. In general, the agreement between calculation and measurement for the SM-2 mockup core is quite good. A high degree of con-

confidence in the predicted nuclear behavior of the reference SM-2 core may be expressed since the same techniques applied to the burnup behavior of the SM-1 Core I have generally predicted measured data extremely well.

In order to further reduce the possible uncertainties in the nuclear behavior of the SM-2 and to advance the analysis work of all APPR-type cores in general, the following recommendations are made:

1. Further investigation of the effects of boron on the surface vs. in the fuel matrix should be made. During fabrication of the SM-2 core, the first 50 plates are to be used for critical experiment checks. The reactivity effect should be measured and calculated in several locations of the core at specified bank positions for both cold and hot mockup cores.

2. Fuel elements or fuel plate samples which have been irradiated and removed for chemical analyses should be analyzed for both B-10 and U-235. Measurements of B-10 burnup vs. fuel burnup would yield a verification of the analytical models used to calculate the maximum reactivity to be controlled in the SM-2 core.

3. A detailed uncertainty analysis of the SM-2 core should be made to determine the minimum and maximum reactivities to be expected during core life.

4. A study of the analytical models should be made, including:

a. A review of the cross section files for the MUFT code, especially stainless steel.

b. Application of flux-weighted axial calculations to predict bank worth.

c. Review of validity of assumption that poisoning effect of the control rods is independent of bank position or fuel burnup.

d. Calculations of low excess reactivity SM-2 cores to check the analytical models.

e. Calculations of reactivity effects of reflector, flux suppressors, material worths, and substitution effects.

5. Additional reactivity measurements and analysis should be made in the hot mockup to determine effects of flow divider, flux suppressors, and reflector effects.

6. Bank calibrations should be made in both cold and hot mockup cores, as a function of core life.

7. A detailed study of heating vs. aluminum addition for measurement of temperature coefficients should be made.

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