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

**FLUX AND POWER DISTRIBUTIONS
FOR THE SM-2
REFERENCE AND CRITICAL
EXPERIMENT CORES**

ALCO PRODUCTS, INC.

NUCLEAR POWER ENGINEERING DEPARTMENT

P. O. BOX 414, SCHENECTADY 1, N. Y.

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By:

B. E. Fried
M. R. Alford
J. P. Oggerino

Approved by:

E. F. Phelps, Project Engineer

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ALCO PRODUCTS, INC.
Nuclear Power Engineering Dept.
Post Office Box 414
Schenectady 1, N. Y.

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ABSTRACT

This report contains a detailed analysis of the power distributions in the SM-2 experimental core at 68°F and the SM-2 reference core at 510°F. This work supersedes the power distribution calculations presented in APAE No. 69. The calculated distributions for the experimental core are normalized to measured data wherever possible in order to obtain corrections factors for application to the reference core. The overall power distributions were calculated by synthesis of one-dimensional axial calculations with two-dimensional radial calculations.

The variation of the power distribution with fuel burnup is also presented. In order to improve the agreement between measured and calculated axial power distributions, flux-weighting the nuclear parameters in the rods-in and rods-out regions was investigated.

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SUMMARY

This report presents the final power distribution for the SM-2 reference core. ⁽¹³⁾ This work supersedes the power distribution analysis presented in the SM-2 Core and Vessel Design Analysis Report. ⁽¹³⁾

The overall power distribution in the core was calculated by synthesis of one-dimensional axial calculations (WINDOWSHADE and VALPROD) and two-dimensional radial calculations (PDQ). Variations of the power peaking factors with fuel burnup were calculated by use of the TURBO and CANDLE-2, IBM-704 codes.

In general, the calculated radial intercell power distribution under-estimates the measured values, whereas the calculated axial distribution over-estimates the measured values. Therefore, correction factors, to account for control rod effects and the non-separability of the axial and radial distributions, were obtained from comparisons of calculated and measured data for the experimental core; these correction factors were then applied to the reference core calculations.

The axial power distribution was calculated both by the WINDOWSHADE code and by an axial VALPROD code using flux-weighted nuclear constants for the rods-in and rods-out regions; the flux weighting method results in better agreement with measurements. For the hot, reference core, the maximum radial hot spot factor at 0 MWYR was found to be 2.00 and occurred in element 44 (control rod C). The axial peak-to-average ratio (calculated by axial VALPROD with flux-weighted parameters) was found to be 1.59 and occurred at 8 in. above the bottom of the active core. The Eu_2O_3 integral flux suppressors effectively eliminated the power spike at the bottom of the core. Therefore, the overall maximum-to-average power in the core at 0 MWYR is 3.2.

Due to the movement of the control rod bank, the axial peak increases as the radial peaks decrease during the early stages of core life; the overall power peaking in the core increases to a maximum at an average fuel burnup of 9% (6.5 MWYR) and then decreases to the end of core life. The maximum overall peak-to-average power ratio is calculated to be 3.5 as compared to the value of 3.2 at 0 MWYR.

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INTRODUCTION

The SM-2 is a high performance PWR utilizing fuel elements and control rods similar to those of the SM-1.⁽¹³⁾ The SM-2 core is designed to operate at 28 MWT corresponding to an average power density of about 200 watts/cm³. The relatively high fuel loading and the presence of non-fuel regions in the core results in high local power peaking. These high local power peaks place stringent coolant requirements upon the SM-2. Therefore, an accurate power distribution within the core is needed in order to perform accurate thermal analyses. The approach used to obtain this power distribution was as follows:

- a. Mockup Measurement - Detailed power mapping measurements were obtained by fission foils at the Alco Critical Facility within an experimental mockup of the SM-2 Core.⁽¹⁰⁾ These measurements were made at room temperature (68°F).
- b. Analysis of Measurements - Axial and two-dimensional radial power distributions were calculated for the mockup core and compared to measurements to obtain correction factors.
- c. Analysis of Reference Core - Axial power distributions were calculated and synthesized with calculated two-dimensional radial power distributions for the SM-2 reference core, at the operating temperature of 510°F. Correction factors were applied to obtain the best estimate of the actual power distribution within the core.

From the best estimate of the power distribution in the SM-2 reference core, power peaking factors ⁽⁹⁾ which are needed to perform the thermal analyses were calculated. The power peaking factors needed, include:

- a. Power generation rate at the hottest spot in each element normalized to an average radial power of 1 over the entire core.
- b. Power generation rate for the worst plate in each element normalized to an average radial power of 1 over the entire core.
- c. Nuclear uncertainty factors.
- d. Fraction of the total power generated in the fuel plates.
- e. Fraction of the total power generated in the core.
- f. Power generation rate for the nominal channel in the nominal element.

This report describes the analytical models employed, comparisons of analytical to measured power distributions, the correction factors obtained, and the final power distribution (power peaking factors) for the reference SM-2 design.⁽¹³⁾

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1.0 CALCULATIONAL MODELS^{(9), (13)}

Flux and power calculations for the SM-2 experimental and references cores were obtained using the PDQ, CANDLE-2, and TURBO codes for the IBM-704 computer.

1.1 MACHINE CODES

1.1.1 PDQ ⁽¹⁾

The PDQ, IBM-704 code is a two-dimensional, multiregion code which solves from one to four lethargy groups in either x-y or r-z geometry. It finds a discrete numerical approximation to the few-group, time independent (steady-state), neutron diffusion equations. Output includes pointwise flux and power distributions and K_{eff} of the core.

1.1.2 CANDLE-2 ⁽²⁾

The CANDLE-2, IBM-704 Code is a one-dimensional, few group, diffusion theory, lifetime depletion code designed for the study of slab, cylindrical, and spherical reactors. The code estimates reactor lifetime for a given fuel loading and determines the time dependence of fuel distributions and flux shapes. Criticality is maintained during the lifetime of the reactor either by adjusting a variable poison cross section or by varying the transverse buckling. In order to permit treatment of axial depletion in slabs and cylinders, provisions have also been made for controlling reactivity by moving the interface between a poisoned (rodded) and an unpoisoned (unrodded) region.

The method of calculation for the CANDLE is similar to that used in the NUB-1, ⁽³⁾ IBM-650 code, in that the effect of the control rods and the control rod fuel elements are replaced by equivalent poisoning factors. In addition, the burnup calculation is done separately in the radial and axial directions. The CANDLE-2 code permits a pointwise burnup with new flux distributions calculated for each time step.

1.1.3 TURBO ⁽⁴⁾

The TURBO, IBM-704 code, is a two or four group depletion calculation in two dimensions and is the direct counterpart of the one-dimensional code, CANDLE. The neutron flux values are computed in either x-y or r-z geometry by using a modification of PDQ.

The TURBO code is especially useful in obtaining an estimate of local power peaking as a function of core lifetime. The one-dimensional codes are not capable of predicting the variation of the local power peaking (in

the corners of the elements, near the flow divider, etc.) as a function of fuel burnup. For this reason a TURBO calculation was performed on the SM-2 core. Knowledge of the most adverse power distribution is essential in determining the required coolant flow rate through the core.

1.1.4 VALPROD⁽¹⁷⁾

VALPROD is a multigroup, multiregion, one-dimensional IBM-650 code which solves the diffusion equations in slab, cylindrical or spherical geometry. Because of its versatility, this code was used to calculate reactivity and the axial flux and power distributions with flux-weighted cross-sections.

1.1.5 WINDOWSHADE⁽¹²⁾

The WINDOWSHADE solves for a critical rod bank position using a thermal absorption cross-section to represent the rod bank. The code is limited to solving the two-group diffusion equations in slab geometry and suffers from any inaccuracy in the "windowshade" model.

1.2 CORE CONFIGURATION

The core lattice designation for the SM-2 (10), (13) is shown in Fig. 1-1. There are a total of 45 cells with 38 fixed fuel elements (Fig. 1-6) and seven movable control rod fuel elements (Fig. 1-7). Figure 1-1 shows the control rod fuel elements in an open array. This configuration was chosen instead of a closed array because of both nuclear and mechanical design considerations.⁽⁹⁾ The open array proved to be slightly better for various stuck rod conditions.^(9,10)

1.2.1 Rods-Out Region

Figure 1-2 shows a schematic cross section of the SM-2 Experimental Core as used for a rods full-out (unrodded region of the core) PDQ (x,y) calculation. The absorber sections are fully withdrawn so that the control rod fuel elements are fully inserted into the core.

Figure 1-3 shows a schematic cross section of the SM-2 Reference Core as used for the rods-out (unrodded region of the core) PDQ (x,y) calculation. This core contains a flow divider which is utilized in the two-pass flow design.

1.2.2 Rods-In Region

Figure 1-4 shows a schematic cross section of the SM-2 Experimental Core as used for a rods full-in (rodded region of the core) PDQ (x,y) calculation. The absorber sections are fully inserted, pushing the control rod fuel elements out into the bottom reflector. Figure 1-5 shows a schematic cross section of the SM-2 Reference Core as used for a rods full-in (rodded region of the core) PDQ (x,y) calculation.

1.3 CALCULATION OF NUCLEAR PARAMETERS

To obtain the fast and thermal nuclear parameters, use was made of the MUFT-III⁽⁵⁾ and P-3, ⁽⁶⁾ IBM-650 codes respectively. The fuel elements were divided into various active and dead regions as shown in Fig. 1-2 to 1-5. The two group parameters of the active and dead regions are tabulated in Table 1-1 for the rods-out experimental core at 68°F and in Table 1-2 for the rods-out reference core at 510°F.

1.3.1 Fixed Elements

Fast group properties were calculated by use of the MUFT-III, IBM-650 code, which solves the Fourier transform of the slowing down distribution from a point source in an infinite medium. The P-1 Selengut-Goertzel approximation for slowing down by hydrogen and inelastic scattering as described by the Weisskopf statistical model was used. The fast group properties of both the active and dead regions of the fixed elements were calculated by the MUFT-III code. The slowing down spectrum for various material compositions are shown in Fig. 1-9 through 1-10. These figures show that the neutron spectrum in the SM-2 Core at 510°F is similar to that of pure water at the same temperature. In stainless steel, however, the spectrum is quite different. This is important since the one group fast cross-sections are averaged over the neutron spectrum; therefore different average cross-sections will be calculated for the same material depending on the neutron energy spectrum in the region. These microscopic cross-sections are used in the CANDLER-2 code.

The P₃-theory IBM-650 code was used to calculate the flux weighted thermal properties of the fixed element active region. The thermal microscopic cross-sections of the fixed element dead region were calculated by finding the atomic number density of each material in the homogenized dead region and multiplying by the respective thermal microscopic cross-sections. This thermal data was obtained by averaging over a hardened Maxwell-Boltzmann thermal flux spectrum.⁽⁷⁾ Tables 1-5 and 1-6 list the microscopic cross-sections used for calculating the thermal properties of each material in the SM-2 core. The fast and thermal properties of the experimental and reference cores are tabulated in Tables 1-1 and 1-2 respectively.

1.3.2 Control Fuel Elements

The fast group properties of the active and dead regions of the control fuel elements were calculated by the MUFT-III code. The active region of the control fuel elements, although smaller than in the fixed fuel elements, has the same composition as the active region of the fixed elements; therefore, the fast and thermal properties will be the same as those of the fixed element active region.

The dead region of the control fuel elements was broken up into two sections. One section includes part of the control rod basket, the side plates, the fuel plate dead edges, and water, while the section parallel to the fuel plates includes just the remaining portion of the control rod basket and the remaining water (See Fig. 1-2 & 1-3). The thermal properties for these two dead regions were calculated in the same manner as the thermal properties of the fixed element dead region. Again, the thermal cross-sections were averaged over a hardened Maxwell-Boltzmann distribution. The fast and thermal properties are tabulated in Tables 1-1 and 1-2.

1.3.3 Pure Water and Steel Regions

The two-group properties for pure water and type 347 stainless steel at 68°F and 510°F are given in Tables 1-3 and 1-4 respectively. The fast and thermal properties were calculated in the same manner as the properties of the dead regions of the fixed elements described in the previous section.

1.3.4 Absorber Sections

A diagram of the control rod absorber section is shown in Fig. 1-8. Boron was used as the absorbing material in the Sm-2 experimental core whereas europium oxide is the absorber material in the reference core.

The fast properties of both the boron and europium absorbers were initially assumed to be the same as those of stainless steel (Table 1-3 and 1-4).

Making this assumption introduces a calculational error which tends to underestimate the control rod bank worth. Work currently being done to resolve this discrepancy includes various methods for describing the resonance absorption in the rods. In this report a method reported in WAPD-218(8) was used to determine the effective resonance absorption cross-section of 0.33 cm^{-1} for the control rod absorber section. (See Appendix A). From a rods-in PDQ (x,y) calculation, flux weighted fast and thermal nuclear constants were calculated. (See Appendix B.) This was repeated for a rods-out PDQ (x,y) calculation. These constants were then used in an axial VALPROD calculation (WINDOWSHADE was not used due to limitations of the code), to determine the critical interface position and the axial power distribution.

This position corresponds to the critical rod bank position as calculated by the WINDOWSHADE code using a thermal absorption cross section to simulate the control rod bank.

The thermal cross sections calculated by this method gave essentially the same answers as thermal cross sections calculated by diffusion theory. This leads one to believe that the absorber is completely black to thermal neutrons.

TABLE 1-1
NUCLEAR PROPERTIES OF SM-2 EXPERIMENTAL CORE AT 68°F,
NO XENON - RODS-OUT
(B² = 0.006896)

Parameter	Units	Fixed Elements		Control Fuel Elements *	
		Active Region	Dead Region	Dead Region 1 /	Dead Region 2 //
D _f	cm	1.307954	1.439150	1.300459	1.192521
Σ _a ^f	cm ⁻¹	0.014458	0.003020	0.003861	0.003784
p		0.649165	0.909445	0.877972	0.892292
Σ _{sl} ^{f**}	cm ⁻¹	0.026752	0.030329	0.027782	0.0131344
τ	cm ⁻²	31.738459	43.154199	41.097850	33.948244
νΣ _f ^f	cm ⁻¹	0.018674	0	0	0
K _f		1.291573	0	0	0
D _{th}	cm	0.153330	0.217765	0.219132	0.202430
Σ _a th	cm ⁻¹	0.522375	0.062210	0.076960	0.074480
νΣ _f th	cm ⁻¹	0.797463	0	0	0
K _{th}		1.526610	0	0	0

* Active region of control fuel element is the same as active region of fixed element.

/ Includes the side plates

// Includes the dead region bounded by dead region 1

**

$$\left(\Sigma_{sl}^f = \frac{D_f}{\tau} - \Sigma_a^f \right)$$

TABLE 1-2
NUCLEAR PROPERTIES OF SM-2 REFERENCE CORE AT 510°F
AND 2000 PSIA - RODS OUT
($B^2 = 0.006593 \text{ cm}^{-2}$)

Parameter	Units	Fixed Elements		Control Fuel Elements *	
		Active Region	Dead Region	Dead Region 1 [/]	Dead Region 2 ^{//}
$N^{25} \times 10^{24}$	atoms/cc	0.000761	-	-	-
$N^{28} \times 10^{24}$	atoms/cc	0.000056	-	-	-
$N^{B-10} \times 10^{24}$	atoms/cc	0.000028	-	-	-
$N^{SS} \times 10^{24}$	atoms/cc	0.016914	0.033095	0.032540	0.026014
$N^H \times 10^{24}$	atoms/cc	0.039512	0.031954	0.032296	0.036320
$N^O \times 10^{24}$	atoms/cc	0.021389	0.015977	0.016148	0.018160
τ	cm^2	49.890143	55.846915	55.651741	53.861557
D_f	cm	1.640467	1.445557	1.451207	1.524951
$\sum_a^f$	cm^{-1}	0.014638	0.004637	0.004569	0.003755
$\nu \sum_f^f$	cm^{-1}	0.019298	-	-	-
ρ		0.554816	0.820856	0.824803	0.867378
$\sum_a^{th}$	cm^{-1}	0.358854	0.062224	0.061348	0.051038
$\sum_s$	cm^{-1}	1.384235	1.303632	1.308113	1.368043
$\sum_{tr}$	cm^{-1}	1.389994	1.082127	1.082791	1.090625
$\nu \sum_f^{th}$	cm^{-1}	0.551873	-	-	-
D_{th}	cm	0.239809	0.308035	0.307846	0.305639

* Active region of control fuel elements assumed to be identical to the active region of the fixed elements

[/] Includes the side plates

^{//} Includes the dead region bounded by dead region 1.

TABLE 1-3
PURE WATER AND STEEL NUCLEAR PARAMETERS
FOR EXPERIMENTAL CORE AT 68°F
($B_T^2 = 0.006896$)

<u>Parameter</u>	<u>Units</u>	<u>Pure Water</u>	<u>Pure 304L Steel</u>
τ	cm ²	33.429716	161.908623
D_f	cm	1.621547	1.316621
$\sum_a^f$	cm ⁻¹	0.000486	0.008132
K_f		0	0
$\sum_T^f$	cm ⁻¹	0.048506	0.008132
p		0.989989	0.000019
$\sum_a^{th}$	cm ⁻¹	0.016960	0.193228
$\sum_s$	cm ⁻¹	2.420297	0.888572
$\sum_{tr}^{th}$	cm ⁻¹	1.934569	1.071224
$\nu \sum_f^{th}$	cm ⁻¹	0	0
K_{th}		0	0
D_{th}	cm	0.172303	0.311170
L_{th}^2	cm ²	10.159375	1.610377
$\xi \sum_s$	cm ⁻¹	0.048020	0.000001

TABLE 1-4
NUCLEAR PROPERTIES OF PURE WATER AND PURE STEEL
USED IN REFERENCE CORE AT 510° F
($B_T^2 = 0.006593 \text{ cm}^{-2}$)

<u>Parameter</u>	<u>Units</u>	<u>Pure Water</u>	<u>Pure 347 Stainless</u>
$N^H \times 10^{24}$	atoms/cm ³	0.052358	-
$N^O \times 10^{24}$	atoms/cm ³	0.026179	-
$N^{SS} \times 10^{24}$	atoms/cm ³	-	0.084922
τ	cm ²	53.904750	183.606982
D_f	cm	2.035606	1.490530
$\sum_a^f$	cm ⁻¹	0.000361	0.008118
$\sum_{sl}$	cm ⁻¹	0.037454	0.000001
ρ		0.990439	0.000010
$\sum_a^{th}$	cm ⁻¹	0.009947	0.144092
D_{th}	cm	0.297148	0.326784

TABLE 1-5
THERMAL MICROSCOPIC CROSS SECTIONS (BARNs)
(T = 68°F, E_N = .0331 eV)

Atom	$\bar{\sigma}_s$	$(1 - \mu_o)$	$\bar{\sigma}_a$	$\bar{\sigma}_{tr}$	$\bar{\nu}\bar{\Sigma}_F$
U ²³⁵	9.0	.997165	512.6564	521.630	1065.14
H	34.32	.784	.254164	27.170	-
O	3.9	.958334	0	3.7375	-
B-10*	4.4	.933441	2932.50	2936.6051	-
S.S.	10.44	.988	2.270275	12.586	-

* Based on 19.8 a/o of B-10 in natural Boron

TABLE 1-6
THERMAL MICROSCOPIC CROSS SECTIONS (BARNs)
T = 510°F, E_N = 0.0600

Atom	$\bar{\sigma}_s$	$(1 - \mu_o)$	$\bar{\sigma}_a$	$\bar{\sigma}_{tr}$	$\bar{\sigma}_f$	$\bar{\nu}\bar{\Sigma}_f$
U-235	9.0	0.997165	362.2284	371.2029	755.5832	307.1476
U-238	9.0	0.997201	1.583095	10.5579	-	-
H	28.035	0.6908	0.189971	19.5563	-	-
O	3.9	0.958334	0	3.7375	-	-
B-10*	4.4	0.933441	2195.1091	2199.2162	-	-
SS	10.44	0.988	1.696762	12.0115	-	-

* Based upon 19.8 a/o of B-10 in natural Boron.

1.3.4.1 Diffusion Theory

The thermal properties for the absorber as calculated by diffusion theory ⁽⁹⁾ are given in Tables 1-7 and 1-8 for the experimental and reference core respectively. Again, the thermal parameters were calculated by averaging the microscopic cross sections over a hardened Maxwell-Boltzmann flux spectrum.

1.3.4.2 Equivalent Diffusion Theory

Diffusion theory is inadequate for highly absorbing regions such as the control rod absorber regions. The reason for this is that in the derivation of the diffusion equations, $\sum_s$ is usually considered much larger than $\sum_a$ and it is assumed that $\sum_{\text{total}} = \sum_s$ while $\sum_a = 0$. In an absorber region, $\sum_a$ is of the same order as $\sum_s$ and this assumption is no longer valid. To overcome this difficulty, schemes have been derived in which the absorber regions are treated by various boundary conditions. The transmission and reflection properties of the boundaries are based upon transport theory calculations.

Many of the computation schemes available for flux calculations are based on a diffusion theory approximation. While some codes handle control rod regions by the use of boundary conditions on the flux and current, it is more convenient to specify "effective" diffusion theory parameters for the control rod. These "effective" parameters are only a mathematical device which allows the computer to treat the control rod in the same manner as the other core regions.

The theoretical basis of the method by which the equivalent or "effective" diffusion theory parameters can be found is described in a report of A. F. Henry. ⁽⁸⁾ The "effective" parameters were calculated by the formulae derived in Appendix A and are tabulated in Tables 1-7 and 1-8 for the experimental and reference cores respectively.

In this particular case, the difference in the total control rod worth between diffusion theory ($\sum_a = 37$) and "equivalent diffusion theory" ($\sum_a = 9$) is only 1% Δk with both methods considerably underestimating the experimentally determined control rod worth. This shows that the rods are black to thermal neutrons. It became necessary to apply the "equivalent diffusion theory" method to the resonance group to account for fast absorptions in the rods since the thermally black rods could not account for the complete control rod worth.

TABLE 1-7
THERMAL PROPERTIES OF SM-2 EXPERIMENTAL
CORE - BORON ABSORBER - 68°F

<u>Parameter</u>	<u>Units</u>	<u>Diffusion Theory</u> ⁽⁹⁾	<u>Henry's Method</u> ⁽⁸⁾
N ^{SS}	atoms/cc	0.076358 x 10 ²⁴	0.076358 x 10 ²⁴
N ^B	atoms/cc	0.012539 x 10 ²⁴	0.012539 x 10 ²⁴
$\sum a$	cm ⁻¹	36.943944	8.572055
D _{th}	cm	0.008822	0.000651

TABLE 1-8
THERMAL PARAMETERS OF SM-2 REFERENCE
CORE Eu₂O₃ ABSORBER SECTIONS - 510°F

<u>Parameter</u>	<u>Units</u>	<u>Diffusion Theory</u> ⁽⁹⁾	<u>Henry's Method</u> ⁽⁸⁾
N ^{SS}	atoms/cc	0.049372 x 10 ²⁴	
N ^{Eu}	atoms/cc	0.008983 x 10 ²⁴	
N ^O	atoms/cc	0.013474 x 10 ²⁴	
$\sum a$	cm ⁻¹	22.697663	8.016556
$\sum s$	cm ⁻¹	0.639851	-
D _{th}	cm	0.014749	0.004330

TABLE 1-9
ELUX-WEIGHTED CROSS-SECTIONS OF THE SM-2
EXPERIMENTAL CORE - 68°F

<u>Parameter</u>	<u>Units</u>	<u>Rods-out Region</u>	<u>Rods-in Region</u>
D_f	cm	1.319465	1.349434
τ	cm ²	33.130358	30.526037
P		0.684977	0.643262
K_f		1.233710	0.884020
D_{th}	cm	0.165875	0.066814
$\sum_a^{th}$	cm ⁻¹	0.404863	0.319561
K_{th}		1.461677	1.205312

TABLE 1-10
FLUX WEIGHTED CROSS-SECTIONS OF THE SM-2
REFERENCE CORE - 510°F

<u>Parameter</u>	<u>Units</u>	<u>Rods-out Region</u>	<u>Rods-in Region</u>
D_f	cm	1.614721	1.644450
τ	cm ²	50.397034	45.861338
P		0.583303	0.559138
K_f		1.262002	0.903276
D_{th}	cm	0.248811	0.190918
$\sum_a^{th}$	cm ⁻¹	0.309920	0.263553
K_{th}		1.488600	1.164020

TABLE 1-11
CALCULATED AXIAL POWER DISTRIBUTIONS IN SM-2
EXPERIMENTAL CORE - 68°F

P (z)/ P core avg. of 1.0		
<u>Inches from Bottom of Core</u>	<u>Axial VALPROD with Flux-Weighted Nuclear Parameters</u>	<u>WINDOWSHADE using $\sum p$ (Thermal)</u>
0	3.174	3.61
2	1.470	1.686
4	1.772	2.008
4.94	1.821 (Axial Max)	2.045 (Axial Max)
5.9	1.800	1.993
7.9	1.453	1.402
9.9	1.046	0.913
11.9	0.808	0.670
13.8	0.616	0.487
15.8	0.460	0.346
17.8	0.331	0.235
19.8	0.220	0.145
21.75	0.413	0.109

FIGURE 1-1

OPEN SEVEN ROD ARRAY

(CONTROL RODS A, B, C, D, E, F, G)

FIGURE 1-2
SM-2 EXPERIMENTAL CORE-RODS OUT AS
SEEN BY THE PDQ (X,Y) CODE

FIGURE 1-3

DIAGRAM OF SM-2 REFERENCE CORE AS SEEN BY THE PDQ(X,Y)
CODE- RODS FULL OUT

FIGURE 1-4
SM-2 EXPERIMENTAL CORE - RODS IN
AS SEEN BY THE PDQ (X,Y) CODE

FIGURE 1-5
S M -2 REFERENCE CORE-RODS FULL IN
AS SEEN BY THE PDQ(X,Y) CODE

[illegible]

PRELIMINARY

Figure 1-9

Figure 1-10

2.0 INITIAL FLUX AND POWER DISTRIBUTIONS

2.1 SM-2 EXPERIMENTAL CORE - 68°F - RODS FULL OUT

Two-dimensional flux and power calculations for the experimental mock-up core were performed by use of the PDQ IBM-704 code. An extensive flux and power mapping of the SM-2 experimental core was performed during the SM-2 flexible critical experiments. (10) Analytical predictions of the radial and axial power distributions were compared with experimental data at 68°F in order to obtain correction factors which were applied to the SM-2 reference core at 510°F.

2.1.1 Radial Power Distributions

Figures 2-1, 2-2, and 2-3 show a comparison between PDQ (x, y) calculations and experimental radial distributions (11) for the SM-2 experimental core - 68°F - rods out, with a stainless steel reflector. The measured values were normalized to the calculated value at the core center to eliminate the effect of the axial power distribution; this assumes the same axial power shape through each element. Agreement is good except at the edges of the elements where the calculated value underestimates the power peak considerably. This agrees with the usual diffusion theory results. Figure 2-3 is of particular interest since it shows the power distribution across a plane which passes through the edges and corners of some of the hottest elements in the core.

These graphs illustrate that the PDQ (x, y) calculations can predict the shape of the local power distributions very well except at the edge of the fuel next to the dead regions. A correction factor called F_{local} correction is applied to the calculated value at the edge to bring it into agreement with the measured data. This factor is described in Section 2.3.2.

2.1.2 Axial Power Distributions

Traverses down the center of each element were made on the experimental mockups and compared to the calculated axial power distribution. The homogenized core constants used in the axial WINDOWSHADE calculation are listed in Table 2-1.

Figures 2-4 to 2-6 show the axial power distributions for the SM-2 experimental core. The calculated axial power distribution does not agree with the measured data. One explanation is that the homogeneous rod poison depresses the calculated power more than a discrete bank of 7 rods, thus raising the peak-to-average power. The calculated axial power distribution was multiplied by the PDQ (x, y) power at the center of each element for comparison with the measured data. The difference in the curves (measured and calculated

poison method) reflects the correction factor F_{rods} . This factor is described in Section 2.3.1.

Another calculation of the axial power distribution was performed using the flux-weighting method. (See Appendix B.) An axial VALPROD calculation was performed on the IBM-650 computer using constants for the rods-in and rods-out regions obtained from the appropriate PDQ (x,y) calculations. The fast and thermal constants for each axial core region were weighted by the fast and thermal fluxes respectively. (See Tables 1-9 and 1-10.) A boundary search for the critical interface position was run and was not significantly different from the position predicted by the thermal poison technique; however, the calculated axial power distributions were in much better agreement with the measured axial power distributions. (See Table 1-11 and Figs. 2-4 to 2-6.) The improved agreement will bring the F_{rods} correction factors closer to unity.

2.2 SM-2 EXPERIMENTAL CORE - 68°F - RODS FULL-IN

Two-dimensional flux and power calculations for the SM-2 experimental core at 68°F, rods full-in, were calculated using the PDQ (x,y) IBM-704 code. The calculated power distributions through the central radial planes of the core, both parallel and perpendicular to the fuel plates, are given in Fig. 2-7 and 2-8. The relative thermal flux distributions through the central radial planes, both parallel and perpendicular to the fuel plates are shown in Fig. 2-9 and 2-10. The relative fast flux, parallel and perpendicular to the fuel plates are shown in Fig. 2-11 and 2-12.

A comparison of the power at the center of each element for the SM-2 experimental core at 68°F with rods full-in and rods full-out is given in Table 2-2. The maximum ratio of the power at the center of an element between the rods in and rods out case is 1.50 in element number 76. The minimum ratio is 0.81 in element 54 which lies between two control rods. Element 46 is also located between two control rods and has a ratio of rods in to rods out power of 0.85. This shows the effect of the control rods nearby fuel elements.

It should be noted in Fig. 2-7 that the power in the element nearest the control rod peaks considerably. This apparently should not happen in the vicinity of a control rod but one must remember that the power is mainly dependent on the thermal flux and due to the water in the dead region of the fixed fuel element and around the control rod basket, the thermal flux peaks quite highly compared to its value in the absorber region. In Fig. 2-10, where the thermal flux is shown perpendicular to the fixed fuel elements, no such power peaking exists. This is because there is no dead region in the fixed elements perpendicular to the fuel plates. Also, in Fig. 2-8, which shows the power distribution perpendicular to the fuel plates, no power peaking exists near the absorber regions.

TABLE 2-1
SM-2 EXPERIMENTAL CORE - 68°F,
HOMOGENIZED CONSTANTS

<u>Parameter</u>	<u>Units</u>	<u>Fixed Element</u>	<u>Control Element</u>
$\sum_a^{th}$	cm ⁻¹	0.414939	0.325804
$\sum_s^{th}$	cm ⁻¹	2.000226	1.955282
$\sum_{tr}^{th}$	cm ⁻¹	2.037948	1.920510
$\nu \sum_f^{th}$	cm ⁻¹	0.611276	0.449366
D_{th}	cm	0.163563	0.173565
L_{th}^2	cm ²	0.394187	0.532728
K_{th}		1.473173	1.379251
τ	cm ²	33.105704	33.541844
D_f	cm	1.308637	1.280208
$\sum_a^f$	cm ⁻¹	0.015509	0.013522
$\nu \sum_f^f$	cm ⁻¹	0.0020019	0.016415
K_f		1.290671	1.213948
p		0.607667	0.645724
$\xi \sum_s$	cm ⁻¹	0.024020	0.024645

Figure 2-1

Figure 2-2

Figure 2-3 Calculated and Measured Power Distributions through 3.73 Cm plane (plate r) parallel to Fuel Plates - SM-2 Experimental Core - 68°F - SS Reflector

Figure 2-4 Relative Axial Power Distributions vs. Distance from Top of SM-2 Core

Figure 2-5 Relative Power Distribution vs. Distance from Top of SM-2 Core

Figure 2-6 Relative Power Distributions vs. Distance from Top of SM-2 Core

TABLE 2-2
COMPARISON OF RELATIVE POWER WITH RODS-IN TO POWER
WITH RODS-OUT NEAR CENTER OF ELEMENT FOR SM-2
EXPERIMENTAL CORE - 68°

<u>Element No.</u>	PDQ Near Center of Element		Ratio $\frac{\rho_{in}}{\rho_{out}}$
	<u>(Rods-Out)</u>	<u>(Rods-In)</u>	
45	1.374	1.161	0.84
46	1.122	0.956	0.85
47	0.791	0.768	0.99
54	1.384	1.121	0.81
55	1.294	1.163	0.90
57	0.737	0.736	1.0
65	1.057	1.155	1.09
66	0.847	1.020	1.20
67	0.579	0.728	1.26
74	0.792	0.920	1.16
75	0.737	0.992	1.35
76	0.576	0.862	1.50

Figure 2-7

Figure 2-8

CALCULATED THERMAL FLUX DISTRIBUTION THROUGH
CENTRAL RADIAL PLANE PARALLEL TO FUEL PLATES
SM-2 EXPERIMENTAL CORE - 68°F - RODS FULL IN

Figure 2-9

CALCULATED THERMAL FLUX DISTRIBUTION THROUGH CENTRAL RADIAL PLANE
 PERPENDICULAR TO FUEL PLATES SM-2 EXPERIMENTAL CORE 68°F -
 RODS FULL IN

Figure 2-10

FAST FLUX DISTRIBUTION THROUGH
CENTRAL RADIAL PLANE PARALLEL TO
FUEL PLATES SM-2 EXPERIMENTAL
CORE 68°F RODS FULL IN

Figure 2-11

FAST FLUX DISTRIBUTION THROUGH CENTRAL RADIAL
PLANE PERPENDICULAR TO FUEL PLATES SM-2
EXPERIMENTAL CORE - 68°F - RODS FULL IN

Figure 2-12

2.3 CORRECTION FACTORS AT 68°F

2.3.1 Factor F_{rods}

The correction factor, F_{rods} , is used to account for the effect of the control rods on the radial power distribution as well as differences between calculations and experiment. The rods are located in the central region of the core and tend to shift the power distribution from the central elements to the outer elements over the entire core. Comparisons of calculated vs. measured axial power distributions of the SM-2 experimental core at 68°F are given in Fig. 2-4 to 2-6 for various fuel elements. The experimental points were taken down the centerline of each element and have been normalized to a core average of 1.0. The analytical distributions are also normalized to a core average of 1.0. These distributions were obtained by multiplying the axial power distribution, calculated using the WINDOWSHADE code (12) for the SM-2 experimental core at 68°F, by the value of the radial power distribution calculated by the PDQ code at the center of each element. Figures 2-1 and 2-2.) The difference between the calculated and measured distribution reflects the correction factor, F_{rods} .

The expression for calculating F_{rods} is:

$$F_{\text{rods}} = \frac{\left[\frac{P(x, y, z) \text{ measured at the center of each element}}{P(x, y, z) \text{ measured core average of 1.0}} \right]}{\left[\frac{P(x, y, z) \text{ calculated at the center of each element}}{P \text{ calculated core average of 1.0}} \right]}$$

These factors are tabulated in Table 2-3.

The correction factors, F_{rods} and $F_{\text{local correction}}$ (Section 2.3.2) are taken at 5 in. from the bottom of the core because the slope of the axial distribution as seen in Fig. 2-4 to 2-6 at this point is flatter than at any other point. Choosing this position decreases the probability of a counting error due to mislocation of the foils. However, other axial planes were investigated and the comparisons are consistent with the data at the 5 in. plane. The rods were out only 7 in. in the experimental core.

2.3.2 The $F_{\text{local correction}}$ Factor

The local peaking correction factor, $F_{\text{local correction}}$, was calculated at the hottest spot of the element. The hottest spot usually occurs at the corners of the elements. These correction factors were obtained from a comparison of the calculated and measured power distributions of the SM-2 critical experiment core at 68°F.

TABLE 2-3
 F_{rods} CORRECTION FACTORS FOR THE SM-2 EXPERIMENTAL
CORE 68°F - SS REFLECTOR - O MWYR

<u>Element No.</u> (Quadrant 4)	<u>Element No.</u> (Quadrant 1)	<u>P(x, y) PDQ</u> <u>Center of Element</u>	<u>P(x, y) $P(z)_{\text{max}}$</u> <u>Center of Element</u>	<u>* Measured</u> <u>at</u> <u>center at 5 in.</u>	<u>F_{rods}</u> <u>at 5 in.</u>
44	44	1.43	2.60	2.43	0.93
45	43	1.38	2.51	2.24	0.89
46	42	1.12	2.04	1.83	0.90
47	41	0.73	1.32	1.15	0.87
54	34	1.38	2.51	2.20	0.88
55	33	1.29	2.35	2.11	0.90
57	31	0.74	1.35	1.18	0.87
65	23	1.06	1.93	1.78	0.92
66	22	0.85	1.55	1.43	0.92
67	21	0.58	1.06	0.95	0.90
74	14	0.75	1.37	1.28	0.93
75	13	0.74	1.35	1.15	0.85
76	12	0.58	1.06	0.90	0.85

* $P(z)_{\text{max.}}$ = 1.821 (Calculated by Axial VALPROD)

TABLE 2-4
LOCAL PEAKING IN CORNERS - SM-2 EXPERIMENTAL CORE
68°F - SS REFLECTOR, O MWYR

<u>Element No.</u>	<u>P corner Calculated P center</u>	<u>P corner measured at 5 in. P center</u>	<u>F_{local} correction At 5 in.</u>
44	1.59	1.81	1.14
45	1.61	1.88*	1.17*
46	1.76	2.06	1.17
47	1.96	2.14*	1.17*
54	1.76	1.97	1.12
55	1.72	1.92	1.12
57	1.96	2.26	1.15
65	1.84	2.11	1.15
66	2.18	2.40	1.10
67	2.17	2.31*	1.09*
74	2.04	2.26	1.11
75	1.97	2.49	1.26
76	2.12	2.64	1.25

* Peak does not occur at corner

The formula for calculating the factor $F_{\text{local correction}}$ is:

$$F_{\text{local correction}} = \frac{\left[\frac{P(x, y, z) \text{ measured at the corner of each element}}{P(x, y, z) \text{ measured at the center of each element}} \right]}{\left[\frac{P(x, y) \text{ calculated at the corner of each element}}{P(x, y) \text{ calculated at the center of each element}} \right]}$$

These factors are also calculated at an axial distance of 5 in. from the core bottom and are tabulated in Table 2-4.

Both correction factors, F_{rods} and $F_{\text{local correction}}$, are assumed to remain constant with temperature and thus can be applied directly to the calculations of the SM-2 reference core at 510°F. This assumption is conservative since the power peaking at 510°F is less than at 68°F, due primarily to fewer hydrogen atoms in the dead regions. This would reduce the discrepancy between calculated and measured data.

The correction factors were separated to be consistent with previous techniques; however, they could be combined to obtain more simple expressions for corner peaking.

2.4 REFERENCE CORE - 510°F - RODS OUT

Two-dimensional flux and power calculations for the SM-2 reference core at 510°F were calculated by use of the PDQ, IBM-704 code. The calculated power distributions through the central radial plane, both parallel and perpendicular to the fuel plates are given in Fig. 2-13 and 2-14, respectively. Figure 2-15 shows the relative power distribution through the plane passing through the last plate of each fixed element. (The last control rod plate was projected onto this plane). These are the hottest points in the core. The relative thermal flux distributions through the central radial plane, both parallel and perpendicular to the fuel plates are given in Fig. 2-16 and 2-17, respectively. The relative fast flux distribution is shown in Fig. 2-18.

The absolute flux, both thermal and fast, is given by the following expression:

$$\phi_{\text{abs}} = \frac{\nu \delta P \phi'}{4 H S}$$

where:

ν = 2.46 neutrons produced/fission

δ = 3.2175×10^{10} fissions/watt-sec.

P = Power (watts)

ϕ = Relative flux (neutrons/cm²-sec)

H = Active height of core = 55.88 cm

S = Integrated source (neutrons/sec.cm of height for 1/4 core)

$$= \int [\nu \Sigma_f^i \phi_f + \nu \Sigma_{th}^i \phi_{th}]_i dA \quad \begin{array}{l} i = 1, 2, \dots, n, \text{ number of} \\ \text{compositions in the core.} \\ dA = \text{Total area of core} \end{array}$$

For the SM-2 reference core, rods-out at 510°F, the integrated source, S, as calculated by the PDQ code, is 57.81505 neutrons/sec-cm. of height, for 1/4 core. Therefore, for the SM-2 reference core,

$$\phi_{abs} = 6.125 \times 10^6 \times P \times \phi$$

where ϕ is the value of the flux at any point as taken from Fig. 2-16 to 2-18, and P is the value of the power at any level of operation (28 MW for full power in the SM-2 core).

2.4.1 Heat Generation Factors

The PDQ code, employing the properties tabulated in Tables 1-2 and 1-4, was used to calculate the power distribution at 510°F for the Reference Core. In order to obtain the power generation rate for the radial hot spot and worst plate in each element, $Q(\Delta\theta)$ and $Q(\Delta T)$, respectively, it was necessary to first obtain correction factors to bring the calculated values into agreement with the measured distributions. These factors are the same as those given in Section 2.3.

2.4.1.1 Heat Generation Rate at Hottest Spot

The expression for the radial hot spot factor at the start of core life is:

$$Q(\Delta\theta) = P(x, y)_{\max} F_{\text{rods}} F_{\text{local correction}} \quad (1)$$

where

$Q (\Delta \theta)$ = Heat generation rate at the hottest spot in each element, normalized to an average radial power of 1 over the core.

$P(x, y)_{\max}$ = Maximum calculated power generation in each element.

$$F_{\text{rods}} = \frac{\left[\frac{P(x, y, z) \text{ measured at the center of each element}}{P \text{ measured with core average of 1.0}} \right]}{\left[\frac{P(x, y) \text{ } P(z) \text{ calculated at the center of each element}}{P \text{ calculated with core average of 1.0}} \right]}$$

$$F_{\text{local correction}} = \frac{\left[\frac{P(x, y, x) \text{ measured at edge of each element}}{P(x, y, z) \text{ measured at center of each element}} \right]}{\left[\frac{P(x, y) \text{ calculated at edge of each element}}{P(x, y) \text{ calculated at center of each element}} \right]}$$

The values of $Q (\Delta \theta)$ for the reference core elements are given in Table 2-6. The maximum power generation rate occurred in element 44 (control rod C). This table uses the correction factors obtained from the flux-weighted axial calculation which gives better agreement with the measured axial distribution.

2.4.1.2 Total Hot Spot Factor

To calculate the total hot spot factor, one must multiply the radial hot spot factor, $Q (\Delta \theta)$, by the maximum axial power peak $\left[\frac{P(z)_{\max}}{P_{\text{avg of 1.0}}} \right]$. This distribution at 0 MWYR with flux suppressors is shown in Fig. 2-19 and tabulated in Table 2-7. These values are slightly different from those reported in APAE No. 69⁽¹³⁾ because of more recent changes in boron loading.

The SM-2 Reference Core has a 0.5 in. Eu_2O_3 flux suppressor at the bottom of each of the fuel plates in the fixed elements. The primary purpose of these suppressors is to eliminate the power spike at the bottom of the core. The constants for the Eu_2O_3 suppressors are given in Table 2-8.⁽¹³⁾ The worst axial peak at 510°F, no xenon, and 0 MWYR for the reference core occurred at 8 in. above the bottom of the core, where $P_{\max} / P_{\text{Avg.}} = 1.72$.

TABLE 2-5
AVERAGE AND MAXIMUM POWER GENERATION
IN EXPERIMENTAL CORE, 68°F - 0 MWYR

Quarter Core Cross Section

Stationary
Fuel Element

Control Rod
Fuel Element

Element	Average Power - $\frac{*Q(\Delta T)}{F}$			Maximum Power - $\frac{*Q(\Delta \theta)}{F}$		
	Cal.	Meas.	$\frac{\text{Meas.}}{\text{Cal.}}$	Cal.	Meas.	$\frac{\text{Meas.}}{\text{Cal.}}$
74	0.89	0.84	0.94	2.89	2.92	1.01
75	0.88	0.81	0.93	2.66	2.87	1.08
76	0.69	0.65	0.94	2.24	2.36	1.05
65	1.18	1.19	1.01	3.55	3.76	1.06
66	0.97	0.97	0.99	3.36	3.45	1.02
67	0.63	0.58	0.92	2.29	2.20	0.96
54	1.39	1.42	1.02	4.35	4.32	0.99
55	1.32	1.28	0.97	4.04	4.04	1.00
57	0.76	0.73	0.96	2.64	2.65	1.00
45	1.38	1.35	0.98	4.08	4.21	1.03
46	1.15	1.19	1.04	3.82	4.07	1.07
47	0.83	0.82	0.99	2.64	2.63	1.00
64	0.60	0.55	0.92	3.61	3.59	0.99
56	0.55	0.51	0.92	3.57	3.47	0.97
44	0.76	0.68	0.89	4.13	4.39	1.06

* Values normalized to a core average = 1.0

TABLE 2-6
SM-2 HOT SPOT FACTORS
(SM-2 REFERENCE CORE - 510°F - SS REFLECTOR, 0 MWYR)

Element	$P(x,y)$ max. Calculated	$\overline{P}$ avg. Hot Plate	F_{rods}	F_{Local} Correction	$Q(\Delta\theta)$	$Q(\Delta T)$
44	1.89	1.72	0.93	1.14	2.00	1.82
45	1.83	1.42	0.89	1.17*	1.90	1.48
46	1.64	1.36	0.90	1.17	1.73	1.43
47	1.49	1.09	0.87	1.17*	1.52	1.11
54	1.89	1.72	0.88	1.12	1.87	1.70
55	1.79	1.40	0.90	1.12	1.81	1.41
57	1.48	1.08	0.87	1.15	1.48	1.08
65	1.59	1.24	0.92	1.15	1.69	1.31
66	1.51	1.23	0.92	1.10	1.53	1.24
67	1.05	0.70	0.90	1.09*	1.03	0.69
74	1.48	1.24	0.93	1.11	1.53	1.28
75	1.38	1.06	0.85	1.26	1.48	1.13
76	1.01	0.74	0.85	1.25	1.07	0.78

* Peak does not occur at corner

$$P(z)_{max.} = 1.592 \text{ (Calc. By Axial VALPROD)}$$

TABLE 2-7
AXIAL POWER DISTRIBUTION - SM-2 REFERENCE CORE
(510°F - NO XENON, 0 MWYR)

<u>Inches from Bottom of Core</u>	<u>Flux-Weighted Constants In Axial VALPROD</u>	<u>WINDOWSHADE With $\sum p$ (Thermal)</u>
0	0.348	0.398
2	0.905	1.037
4	1.252	1.412
6	1.487	1.647
8	1.592	1.719 (Axial Maximum)
10	1.556	1.622
12	1.384	1.352
14	1.011	0.744
16	0.661	0.526
18	0.461	0.360
20	0.301	0.228
22	0.410	0.176

TABLE 2-8
CONSTANTS FOR Eu_2O_3 FLUX SUPPRESSORS*

<u>Parameter</u>	<u>Units</u>	<u>$\text{Eu}_2\text{O}_3 - 510^\circ\text{F}$</u>
D_f	cm	1.423808
τ	cm^2	48.252546
p		0.889188
D_{th}	cm	0.090822
$\sum_a^{th}$	cm^{-1}	1.781200**
$\bar{\sigma}_{a(\text{Eu})}$	cm^2	2517.45×10^{-24}
$\bar{\sigma}_{a(\text{O})}$	cm^2	0
$\bar{\sigma}_{s(\text{Eu})}$	cm^2	8×10^{-24}
$\bar{\sigma}_{s(\text{O})}$	cm^2	3.9×10^{-24}

* Fast constants are the same as for pure Stainless Steel.

** Based on self-shielding factor of 0.6814 obtained from WAPD - 218.(8)

2.4.1.3 Heat Generation in Hottest Plate

To obtain the heat generation rates in the hottest plate in each element, $Q(\Delta T)$, the calculated average power of the hottest plate in each element was multiplied by the correction factors, as in equation (1) of Section 2.4.1.1. The maximum power averaged over a plate was 1.72 and occurred in control rod C and fixed element 54. The maximum value of $Q(\Delta T)$ was 1.82 and occurred in control rod C (element 44).

In addition, it is useful to define the average power generation per fuel element at 510°F. Again, the ratio of the measured power generation in each fuel element to the calculated value determined for the SM-2 Experimental Core at 68°F, (See Table 2-5) is used as a correction factor for the calculated power generation per element at 510°F. (See Table 3-4.) An additional factor must then be applied which accounts for the shift in the radial power distribution with core burnup.

Therefore,

$$\overline{Q(\Delta T)} = \overline{Q(\Delta T)_{\text{Calc.}}} \times \overline{F} \times \overline{F}_B$$

where

$\overline{Q(\Delta T)}$ = average power generation per element

$\overline{Q(\Delta T)_{\text{Calc.}}}$ = calculated average power generation per element at start of life

$\overline{F}$ = $\frac{\text{measured average power per element}}{\text{calculate average power per element}}$

$\overline{F}_B$ = $\frac{\text{calc. power per element at midlife}}{\text{calc. power per element at initial startup}}$

2.4.1.4 Nuclear Uncertainty Factors

The nuclear uncertainty factors and heat release factors were taken to be the same as those used for the SM-1⁽¹⁴⁾ - that is:

$$F_N(\Delta T) = 1.05$$

$$F_N(\Delta \theta) = 1.05^*$$

$$\psi(\Delta T) = 1.00$$

$$\psi(\Delta \theta) = 0.95$$

* The value of $F_N(\Delta \theta)$ was reduced from the previously used value of 1.10⁽¹⁴⁾ to 1.05 due to improved calculational techniques and the availability of a detailed measured power mapping of the SM-2 experimental core.

where

$F_N (\Delta T)$ = nuclear hot spot factor to allow for uncertainties in calculated power distribution in calculation of bulk coolant temperature rise.

$F_N (\Delta \theta)$ = nuclear hot spot factor to allow for uncertainties in the calculated power distribution used in the calculation of the film temperature rise.

$\psi (\Delta T)$ = fraction of total reactor power generated in core.

$\psi (\Delta \theta)$ = fraction of total reactor power generated in the fuel plates.

2.5 REFERENCE CORE - 510°F - RODS FULL IN

Two-dimensional flux and power calculations for the SM-2 reference core at 510°F with rods full-in were calculated using the PDQ, IBM-704 code. The calculated power distributions through the central radial plane, both parallel and perpendicular to the fuel plates, are given in Fig. 2-20 and 2-21, respectively. The relative thermal flux distributions through the central radial plane, both parallel and perpendicular to the fuel plates are shown in Fig. 2-22 and 2-23. The relative fast flux, parallel and perpendicular to the fuel plates, is shown in Fig. 2-24 and 2-25, respectively.

A comparison of the power at the center of each element for the SM-2 reference core at 510°F with rods-in and rods-out is given in Table 2-9. The maximum ratio of the power difference in the regions is 1.45 in element 76. The minimum ratio is 0.81 in element 46. Element 76 lies at the greatest distance from a control rod. Element 46 is located between two control rods. Element 54 is also located between two control rods and has a ratio of rods-in power to rods-out power of 0.82. As in the experimental core, this again reflects the effect of the rods on the radial power distribution, especially on nearby fuel elements.

THEORETICAL POWER DISTRIBUTION THROUGH CENTRAL
 RADIAL PLANE PARALLEL TO FUEL PLATES - SM-2
 REFERENCE CORE - 510°F - SS REFLECTOR
 CONTROL RODS FULL OUT

Figure 2-13

THEORETICAL POWER DISTRIBUTIONS THROUGH CENTRAL
 RADIAL PLANE PERPENDICULAR TO FUEL PLATES
 SM-2 REFERENCE CORE - 510°F - SS REFLECTOR -
 CONTROL RODS FULL OUT

Figure 2-14

Figure 2-15

Figure 2-16

RELATIVE THERMAL FLUX DISTRIBUTION THROUGH CENTRAL RADIAL PLANE
 PERPENDICULAR TO FUEL PLATES - RODS OUT REFERENCE CORE - 510°F -
 SS REFLECTOR - TO GET ABSOLUTE FLUX MULTIPLY ϕ' BY $6.125 \times 10^6 P$
 WHERE P IS POWER IN WATTS

$$\phi_{ABS.} = \phi' \times 6.125 \times 10^6 P$$

Figure 2-17

RELATIVE FAST FLUX DISTRIBUTION
 THROUGH CENTRAL RADIAL PLANE
 PARALLEL TO FUEL PLATES - SM 2
 REFERENCE CORE - 510° F - SS
 REFLECTOR - RODS - OUT

Figure 2-18

Figure 2-19

TABLE 2-9
COMPARISON SM-2 REFERENCE CORE - 510°F - RODS-IN
AND RODS-OUT POWER AT CENTER OF ELEMENT

<u>Element No.</u>	<u>P(x, y) PDQ at Center of Element Rods-Out</u>	<u>P(x, y) PDQ at Center of Element Rods-In</u>	<u>Ratio $\frac{P_{in}}{P_{out}}$</u>
45	1.38	1.15	0.83
46	1.19	0.96	0.81
47	0.80	0.86	1.08
54	1.36	1.12	0.82
55	1.29	1.12	0.87
57	0.74	0.82	1.11
65	1.06	1.13	1.07
66	0.85	1.03	1.21
67	0.58	0.78	1.34
74	0.78	0.97	1.24
75	0.74	0.97	1.31
76	0.58	0.84	1.45

THEORETICAL POWER DISTRIBUTION THROUGH CENTRAL RADIAL PLANE PARALLEL TO
FUEL PLATES - SM-2 REFERENCE CORE - 510° - RODS FULL IN

Figure 2-20

THEORETICAL POWER DISTRIBUTION THROUGH CENTRAL
RADIAL PLANE PERPENDICULAR TO FUEL PLATES -
SM-2 REFERENCE CORE - 510°F - RODS FULL IN

Figure 2-21

RELATIVE THERMAL FLUX THROUGH CENTRAL RADIAL PLANE PARALLEL TO
FUEL PLATES - SM-2 REFERENCE CORE - 510°F - RODS FULL IN

$$\phi_{abs} = 1.063 \times 10^4 P \phi'$$

Figure 2-22

RELATIVE THERMAL FLUX THROUGH CENTRAL RADIAL
 PLANE PERPENDICULAR TO FUEL PLATES - SM-2
 REFERENCE CORE - 510°F - RODS FULL IN

$$\phi_{ABS} = 1.063 \times 10^4 P \phi'$$

Figure 2-23

RELATIVE FAST FLUX - SM-2 REFERENCE
 CORE - 510° - RODS FULL IN - THROUGH
 CENTRAL RADIAL PLANE PARALLEL TO
 FUEL PLATES

Figure 2-24

RELATIVE FAST FLUX - SM-2 REFERENCE
 CORE - 510°F - RODS IN - THROUGH
 CENTRAL RADIAL PLANE PERPENDICULAR
 TO FUEL PLATES

Figure 2-25

3.0 POWER DISTRIBUTION VARIATION WITH CORE BURNUP

The CANDLE-2⁽²⁾ IBM-704 code was utilized to compute the changes in the power distributions with burnup. This code stores fast microscopic cross sections for three fast groups and coalesces them into average cross sections for a single fast group. This coalescing scheme is different from that calculated by the more accurate MUFT - III code.⁽⁵⁾

In order to obtain better one-fast-group constants, fictitious cross sections were used for the removal (slowing down) cross sections in the first and second energy groups. For the remaining parameters, the one-group average cross sections from the MUFT-III code were used for all three energy groups in the CANDLE-2 code. The fast group constants which were stored in the CANDLE-2 code for the SM-2 are listed in Table 3-1.

3.1 GROSS RADIAL AND AXIAL DISTRIBUTIONS - CANDLE-2

The gross radial power distribution in the SM-2 core at 510°F with equilibrium xenon is shown in Fig. 3-1, for a fixed element core with the control rod fuel elements represented by an equivalent thermal absorption cross section, $\sum a_{\text{sub}}$. Figure 3-2 shows the same radial power distribution

with the control rod fuel elements represented by equivalent rings. In both graphs, it is evident that the radial power distribution is improving with burnup. The axial power distribution at 510°F with no xenon is shown in Fig. 3-3, for 0 MWYR and for 12.4 MWYR; the latter represents the deepest rod bank position as calculated by CANDLE-2. The same cases are shown in Fig. 3-4 for the equilibrium xenon operating condition. The maximum-to-average axial power at the deepest bank position has decreased from 1.82 at no xenon to 1.55 for equilibrium xenon. This improvement occurs because the equilibrium concentration of xenon decreases the reactivity of the core by 2.4% ρ at 12.4 MWYR causing the control rod bank to move out by 1.8 inches. At 0 MWYR, the xenon decreased reactivity by 2.7% ρ with the bank moving 3.5 in. further out since the bank is worth less near the top of the core. In every case, as the rod bank moves out of the core, the overall power peaking decreases.

3.2 RADIAL POWER DISTRIBUTION WITH BURNUP - TURBO CODE ⁽⁴⁾

An analysis of the SM-2 reference core, 510°F, clean, using the TURBO Code for the IBM-704 computer was made to study the effect of fuel burnup on power peaking. Since TURBO is a stepwise depletion code, seven small time steps were run in the range of 0 MWYR to 10.1 MWYR (approximately 1/3 core lifetime). Figures 3-5 to 3-10 show graphically the results of this analysis in various positions of the core. Figure 3-11 shows the variation of the largest power peaks with fuel burnup.

TABLE 3-1
3 FAST GROUP MICROSCOPIC CROSS-SECTIONS, SM-2 - 510°F (BARNs)

<u>Element No</u>		<u>Element</u>	<u>Group</u>	<u>σ_{tr}</u>	<u>σ_a</u>	<u>σ_{sl}</u>	<u>σ_f</u>	<u>$\nu\sigma_f$</u>
<u>WAPD (ALCO)</u>								
1	(1)	H	1	0.996891	0	1.662001	0	0
			2	3.726989	0	2.182873	0	0
			3	6.860784	0.004655	1.511389	0	0
2	(7)	O	1	1.846350	0.034520	0.131116	0	0
			2	3.729818	0	0.049194	0	0
			3	3.799867	0	0.024597	0	0
6	(4)	SS	1	1.320650	0.09550	0.025818	0	0
			2	3.481155	0.09550	0.012964	0	0
			3	8.824924	0.185819	0.016594	0	0
18	(18)	U-235	1	5.965728	1.436907	0.022295	1.29903	3.593456
			2	12.493869	2.423453	0.009191	1.902593	4.719076
			3	49.765012	41.491038	0.003798	30.054327	73.873536
29	(9)	B-10	1	0.437606	0.437606	0	0	0
			2	2.156883	2.156883	0	0	0
			3	188.469818	188.469818	0	0	0

TABLE 3-2
CALCULATED POWER PEAKING IN THE SM-2
REFERENCE CORE - 510°F

<u>Element</u>	<u>$P(x, y)_{\text{max.}} / P_{\text{core avg. of 1}}$</u>	
	<u>TURBO CODE - Old Boron Loading</u> <u>Coalesced Constants</u>	<u>PDQ CODE - New Boron Loading</u> <u>MUFT-III Constants</u>
44 (Rod C)	1.246	1.887
54	1.853	1.892

It should be noted that in each case, the radial and local power peaks decrease with core burnup. These power peaks tend to flatten more rapidly at these points since the uranium burnup fraction is substantially higher than elsewhere in the core. Figure 3-12 shows the maximum uranium burnup at these hot spots as a function of the average uranium burnup in the core. It should be noted that the curves are just starting to bend over and flatten for higher core burnups.

3.3 VARIATION OF POWER PEAKING FACTORS WITH BURNUP

The power peaking factors in the SM-2 core at 510°F as calculated by the TURBO and PDQ codes at the beginning of life are listed in Table 3-2 for elements 54 and 44. The TURBO code calculation is for the SM-2 core containing 63.4 gm B-10. The one-fast-group constants were obtained by coalescing 3 fast groups.⁽¹⁵⁾ The SM-2 reference core containing 56.8 gm B-10 was used in the PDQ calculation with constants obtained from the MUFT-III code (Table 3-2). A difference of 2% in power peaking exists between the two methods. The peaking factors go up slightly with a decrease in the boron loading.

The variation of the radial (x, y) power peak with burnup is shown in Fig. 3-11. Figure 3-13 shows the combination of the radial power peak and the axial power peak from the CANDLE-2 calculation as a function of core burnup. The power peak increases by 11% from the beginning of life (burnup, B, equal to zero) to the maximum at burnup = 0.09. These calculations are conservative due to the assumption of a constant self-shielding factor with burnup in the TURBO (x, y) code. The maximum radial heat generation at midlife in each element is listed in Table 3-3 and is obtained by multiplying the data in Table 2-5 by the burnup factor. This is the best estimate of heat generation factors to be used for thermal analyses. Table 3-4 shows the three-dimensional maximum heat generation factor, $P(x, y, z)$, for the SM-2 core at startup and at the most adverse time of life as well as the average power generation per element at startup.

TABLE 3-3
HEAT GENERATION FACTORS SM-2,
NO XE, MIDLIFE, SS REFLECTOR

Element	$Q(\Delta\theta)$ Initial O MWYR	$Q(\Delta T)$ Initial O MWYR	F_{Burnup} Correction	$Q(\Delta\theta)$ Max.	$Q(\Delta T)$ Max.
44 (C)	2.00	1.82	1.11	2.22	2.02
45	1.90	1.48	1.11	2.11	1.64
46	1.73	1.43	1.11	1.92	1.59
47	1.52	1.11	1.11	1.69	1.23
54	1.87	1.70	1.11	2.08	1.89
55	1.81	1.41	1.11	2.01	1.57
57	1.48	1.08	1.11	1.64	1.20
65	1.69	1.31	1.11	1.88	1.45
66	1.53	1.24	1.11	1.70	1.38
67	1.03	0.69	1.11	1.14	0.77
74	1.53	1.28	1.11	1.70	1.42
75	1.48	1.13	1.11	1.64	1.25
76	1.07	0.78	1.11	1.19	0.87

$$F_N(\Delta T) = 1.05$$

$$F_N(\Delta\theta) = 1.05$$

$$\psi(\Delta T) = 1.00$$

$$\psi(\Delta\theta) = 0.95$$

$$L = 22 \text{ in.}$$

$$N = 44$$

$$\Delta z = 0.50 \text{ in.}$$

TABLE 3-4
MAXIMUM AND AVERAGE POWER GENERATION IN THE SM-2
REFERENCE CORE (T = 510°F)

Quarter Core Cross Section

Stationary
Fuel Element

Control Rod
Fuel Element

Element	Max. Power* (B = 0) $Q(\Delta\theta) P(z)$	Max. Power* (B = 9%) $Q(\Delta\theta) P(z)$	Avg. Power* (B = 0) $Q(\Delta T)$	Avg. Power (B = 9%) $Q(\Delta T)$
74	2.38	2.64	0.82	0.83
75	2.36	2.62	0.73	0.74
76	1.70	1.89	0.55	0.56
65	2.69	2.99	1.16	1.15
66	2.44	2.71	0.91	0.90
67	1.60	1.78	0.54	0.55
54	2.98	3.31	1.50	1.47
55	2.85	3.16	1.32	1.29
57	2.36	2.62	0.75	0.76
45	3.02	3.35	1.41	1.38
46	2.75	3.05	1.28	1.27
47	2.37	2.63	0.85	0.86
64	2.60	2.89	1.17	1.16
56	2.50	2.98	1.10	1.09
44	3.19	3.54	1.43	1.37

* Adjusted by correction factors obtained at 68°F.

Figure 3-1 SM-2 Radial Power Distributions - 510°F, Eq. Xenon -
All Fixed Elements $\sum_a$

Figure 3-2 SM-2 Radial Power Distributions - 510°F - Eq. Xenon - Control Rod Fuel Element Rings

Figure 3-3 SM-2 Axial Power Distribution - 510°F - No Xenon

Figure 3-4 SM-2 Axial Power Distributions - 510°F, Eq. Xenon

Figure 3-5

Figure 3-6

Figure 3-7

Figure 3-8

Figure 3-9

Figure 3-10

Figure 3-11

Figure 3-12

VARIATION OF MAXIMUM POWER
AS A FUNCTION OF FUEL BURNUP (B)
(Normalized to the maximum
value at 0 burnup)

Figure 3-13

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APPENDIX A

EQUIVALENT DIFFUSION THEORY PARAMETERS

The method by which equivalent diffusion theory parameters can be found for a control rod region is described in the following section. The theoretical basis for this work is described in a report by A. F. Henry.⁽⁸⁾

Consider a slab of thickness $T = 2t$.

Absorber
Thickness

Let: ϕ^+ and ϕ^- = flux at surface of slab at $+t$ and $-t$, respectively

j^+ and j^- = at $+t$ and $-t$, respectively

Define:

$$\alpha = \frac{j^+ + j^-}{\phi^+ + \phi^-}$$

$$\beta = \frac{j^+ - j^-}{\phi^+ - \phi^-}$$

$$\cosh 2kt = \frac{\beta + \alpha}{\beta - \alpha} \quad (1)$$

$$\cosh^2 2kt = \frac{(\beta + \alpha)^2}{(\beta - \alpha)^2} \quad (2)$$

$$\sinh^2 2kt = \frac{4\alpha\beta}{(\beta - \alpha)^2} \quad (3)$$

$$\sinh 2kt = \frac{2\sqrt{\alpha\beta}}{(\beta - \alpha)} \quad (4)$$

From equations (1) and (4),

$$\tanh 2kt = \frac{2\sqrt{\alpha\beta}}{\beta + \alpha} \quad (5)$$

$$\begin{aligned} \sinh kt &= \sqrt{1/2 (\cosh 2kt - 1)} \\ &= \sqrt{\frac{\alpha}{\beta - \alpha}} \end{aligned} \quad (6)$$

$$D_{\text{eff}} = t \left(\frac{\alpha + \beta}{2} \right) \left(\frac{\tanh 2kt}{\sinh kt} \right) \quad (7)$$

$$D_{\text{eff}} = t \sqrt{\beta (\beta - \alpha)} \quad (8)$$

$$\sinh^2 kt = \frac{\alpha}{\beta - \alpha} \quad (9)$$

$$\begin{aligned} \cosh^2 kt &= \frac{\beta}{\beta - \alpha} \\ \cosh kt &= \sqrt{\frac{\beta}{\beta - \alpha}} \end{aligned} \quad (10)$$

$$\Sigma a_{(\text{eff})} = \frac{2 D (\cosh kt - 1)}{t^2} \quad (11)$$

$$\Sigma_{a_{\text{eff}}} = \frac{2}{t} \left[\beta - \sqrt{\beta(\beta - \alpha)} \right] \quad (12)$$

$$D_{\text{eff}} = t \sqrt{\beta(\beta - \alpha)} \quad (8)$$

Values for α and β have been computed from one velocity transport theory by Maynard (16) for a wide range of slab thickness and for different ratios of scattering to total cross sections (Fig. A-1).

The following equations can be used to correlate α and β to within 1% accuracy, provided that:

$$T \Sigma_T \geq 2.0$$

and

$$\Sigma_s / \Sigma_T \leq 0.2$$

then,

$$\alpha = \gamma - 0.646 \quad -1.15x \quad +0.500 \quad -2.30x$$

$$\beta = \gamma + 0.646 \quad -1.15x \quad +0.500 \quad -2.30x$$

where:

$$\gamma = 0.5 - 0.1952 \left(\frac{\Sigma_s}{\Sigma} \right) - 0.900 \left(\frac{\Sigma_s}{\Sigma} \right)^2$$

$$x = T \left[\Sigma_T - 0.2 \Sigma_s \right] = T \left(\Sigma^a + 0.8 \Sigma_s \right)$$

$$T = 2t, \text{ cm.}$$

$$\Sigma_s, \Sigma_T = \text{scattering and total cross sections, respectively, of the slab - cm}^{-1}$$

APPENDIX B

CALCULATION OF FLUX-WEIGHTED PARAMETERS USING THE PDQ-3(x,y)IBM-704 CODE

The PDQ-3 code will calculate and print out composition integrals of the fast flux, thermal flux, and power of every composition in the core, if requested as an output option of the code.

In order to obtain flux-weighted fast and thermal constants for a core with n compositions, the following equations are utilized:

$$\overline{\Sigma_a^f} = \frac{\Sigma_{a_1}^f \int (\phi_f dA)_1 + \Sigma_{a_2}^f \int (\phi_f dA)_2 + \Sigma_{a_3}^f \int (\phi_f dA)_3 + \dots + \Sigma_{a_n}^f \int (\phi_f dA)_n}{\int (\phi_f dA)_1 + \int (\phi_f dA)_2 + \int (\phi_f dA)_3 + \dots + \int (\phi_f dA)_n}$$

or more briefly,

$$\overline{\Sigma_a^f} = \frac{\sum_{n=1}^n \Sigma_{a_n}^f \int (\phi_f dA)_n}{\sum_{n=1}^n \int (\phi_f dA)_n}$$

where

n = Composition number

$\Sigma_{a_1}^f$ = fast macroscopic absorption cross-section for composition number 1, which is input data to the code

$\int (\phi_f dA)_1$ = integral of the fast flux in composition #1 over the area of composition #1, which is output data of the code.

$\overline{\Sigma_a^f}$ = flux weighted fast macroscopic cross-section over the entire core.

The fast absorption cross section was used as an example in the above equations. The following list shows all the parameters to be calculated:

Fast Constants

$$\overline{\sum_a^f}$$

$$\overline{\sum_{sl}^f} \text{ (Called } \sum_R \text{ by code)}$$

$$\overline{\nu \sum_f^f}$$

$$\overline{\sum_{tr}^f}$$

Thermal Constants

$$\overline{\sum_a^{th}}$$

$$\overline{\nu \sum_f^{th}}$$

$$\overline{\sum_{tr}^{th}}$$

It should be noted that the composition integrated fast flux must be used in calculating the flux-weighted fast parameters and the composition integrated thermal flux must be used for calculating the thermal parameters.

The conversion of these constants into those used more frequently at Alco is:

$$D_f = \frac{1}{3 \sum_{tr}^f}$$

$$D_{th} = \frac{1}{3 \sum_{tr}^{th}}$$

$$\sum_T^f = \sum_a^f + \sum_{sl}^f$$

$$K_{th} = \frac{\nu \sum_f^{th}}{\sum_a^{th}}$$

$$\tau = \frac{D_f}{\sum_T^f}$$

$$p = 1 - \frac{\sum_a^f}{\sum_T^f} = \frac{\sum_{sl}^f}{\sum_T^f}$$

$$K_f = \frac{\nu \sum_f^f}{\sum_a^f}$$

These parameters would now be suitable for use in most ALCO codes, such as PROBLEM 22, VALPROD, WINDOW-SHADE, etc., and directly comparable to those parameters obtained from the MUFT-III code.

APPENDIX C

CALCULATED AND MEASURED POWER DISTRIBUTIONS AROUND THE FLOW DIVIDER IN THE SM-2 EXPERIMENTAL CORE - 68°F

A revised mockup of the SM-2 experimental core at 68°F was analyzed for, among other effects, the change in power peaking when the flow divider was present. Tables C-1 and C-2 list the maximum calculated and measured local power peaking in the fuel elements which are adjacent to the flow divider. In Table C-1, the flow divider is present while in Table C-2 the fuel elements are spaced normally as with no flow divider.

Instead of the power peaking increasing when the flow divider was included, as was expected, the measured as well as the calculated data shows some definite decreases in power peaking. This can be attributed in part to the fact that the rods were about one inch 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 a small amount considering that the water gap between fuel plates is 123 mils.

TABLE C-1

LOCAL POWER PEAKING NEAR FLOW DIVIDER IN
REVISED SM-2 EXP. MOCKUP - 68°F

Through 6 in. Axial Plane

C.R.E. Flux suppressors in exp. data
Rods 1 in. further out.

Element No.	Position		Measured P(x, y, z)	Calculated		F Total Correction
	Plate	Plane (WRP)		P(x, y)	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

TABLE C-2

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		F Total Correction
	Plate	Plane (WRP)		P(x, y)	P(x, y) P(z) P(z) = 1.82	
12	a	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

APPENDIX D
NOMENCLATURE

<u>Parameter</u>	<u>Units</u>	<u>Description</u>
D_f	cm	fast diffusion coefficient
D_{th}	cm	thermal diffusion coefficient
$\sum_a^f$	cm ⁻¹	fast macroscopic cross section
p		resonance escape probability
$\sum_{sl}^f (\xi \sum_s)$	cm ⁻¹	macroscopic slowing down cross section from fast group
$\sum_s$	cm ⁻¹	macroscopic scattering cross section
$\sum_{tr}$	cm ⁻¹	macroscopic transport cross section
$\sum_T^f$	cm ⁻¹	total fast macroscopic cross section
$\sum_f^f$	cm ⁻¹	fast macroscopic cross section
$\sum_f^{th}$	cm ⁻¹	thermal macroscopic cross section
$\overline{\sum}$	cm ⁻¹	flux weighted macroscopic cross section
K_f		total neutrons produced by fast fission neutron absorbed
K_{th}		total neutrons produced by thermal fission per thermal neutron absorbed
τ	cm ²	neutron age
$\sum_a^{th}$	cm ⁻¹	thermal absorption macroscopic cross section
L_{th}^2	cm ²	thermal diffusion length squared
N^{25}	atoms/cm ³	number density of U-235

<u>Parameter</u>	<u>Units</u>	<u>Description</u>
N^{28}	atoms/cm ³	number density of U-238
N^{B-10}	atoms/cm ³	number density of B-10
N^{SS}	atoms/cm ³	number density of stainless steel
N^H	atoms/cm ³	number density of hydrogen
N^O	atoms/cm ³	number density of oxygen
N^{Eu}	atoms/cm ³	number density of europium
B^2	cm ⁻²	total buckling
E_N	ev	energy of the neutron
σ_a	cm ²	microscopic absorption cross section
σ_f	cm ²	microscopic fission cross section
σ_{tr}	cm ²	microscopic transport cross section
ϕ_f	neuts/cm ² -sec	fast flux
ϕ_{th}	neuts/cm ² -sec	thermal flux
$Q(\Delta T)$		power generation for worst plate in each element normalized to core average of 1.0
$Q(\Delta \theta)$		power generation at the hottest spot in each element normalized to a core average of 1.0
$P(z)_{max}$		power generation at worst axial point in the core, normalized to core average of 1.0
$F_N(\Delta T)$		nuclear hot spot factor to allow for uncertainties in calculated power distribution in calculation of bulk coolant temperature rise
$F_N(\Delta \theta)$		nuclear hot spot factor to allow for uncertainties in the calculated power distribution used in the calculation of the film temperature rise

<u>Parameter</u>	<u>Units</u>	<u>Description</u>
$\psi(\Delta T)$		fraction of total power generated in the core
$\psi(\Delta \theta)$		fraction of total power generated in the fuel plates
$\overline{Q(\Delta T)}$		average power generation per element
F_{rods}		correction factor, mostly due to control rod effects
$F_{\text{local correction}}$		local peaking factor
ν		2.46 neutron produced/fission
δ		3.2175×10^{10} fissions/watt-sec
P	watts	power
H	cm	active height of core