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SAXTON CORE II NUCLEAR OPERATIONS SUMMARY

by

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SECTION 1

INTRODUCTION

1.0 Description Of The Saxton Plutonium Program

1.1 Purpose

The purpose of the Saxton Plutonium Program was to develop information concerning the use of plutonium-enriched fuel in pressurized water reactor systems through the design, fabrication, and operation of a partial core of PuO_2 - UO_2 fuel in the Saxton reactor. The in-pile performance of the fuel will be evaluated and a post-irradiation examination of fuel samples will be made. The basic program objective was to achieve as high a burnup in the plutonium fuel as possible during the available period of operation.

1.2 Program Sequence

The nuclear program sequence can be divided into four phases. During phase one, the nuclear design phase, the requirement was to develop the specifications for the partial loading of the mixed-oxide (PuO_2 - UO_2) fuel assemblies to be used in Saxton Core II. It was necessary to determine a plutonium loading that would provide the desired lifetime within the power limitations set by the plant, thermal, and hydraulic design. At the start of the nuclear design work, goals of 10,000 MWD/MTM average burnup in the plutonium fuel with a peak burnup of 20,000 MWD/MTM were established. The second phase consisted of a series of design-oriented, critical experiments conducted at the Westinghouse Reactor Evaluation Center (WREC) utilizing the same fuel rods as those used later in the irradiation test. The purpose of these experiments was to verify the nuclear design of the unirradiated fuel before power operation.

The third phase concerned the operation of the partial plutonium core in the Saxton reactor. During this phase, periodic measurements were made to determine the system reactivity, control rod and boron worth, flux and power distributions, and temperature, pressure, and power coefficients. In addition, a supporting analytic program was carried out to establish the adequacy of available methods in duplicating the observed performance of the core. The fourth phase consisted of a post-irradiation examination of fuel samples and comparison with analytic predictions.

1.3 Scope of the Report

This report describes the work carried out in the third phase, the nuclear operations summary of Saxton Core II. A similar nuclear follow program of $\text{PuO}_2\text{-UO}_2$ fuel is continuing during Core III operation, which began in December, 1969, and will continue until early 1972. WCAP 3385-51, "Nuclear Design of the Saxton Partial Plutonium Core," describes the nuclear design work performed under phases 1 and 2.

1.4 Description of Saxton Core II

The Saxton Core II fuel loading consisted of nine central mixed-oxide ($\text{PuO}_2 - \text{UO}_2$) fuel assemblies and twelve outer UO_2 fuel assemblies. The mixed-oxide contained 6.6 w/o PuO_2 in natural UO_2 . The UO_2 assemblies were enriched to 5.7 w/o U-235. Of the nine plutonium assemblies, two contained vibratory compacted fuel and were installed on the flats in positions D-2 and D-4. The remaining seven assemblies contained pelletized fuel. The plutonium fuel rods were clad with Zircaloy-4 with the exception of some thirty fuel rods which were clad with 304 stainless steel. These special stainless steel rods were distributed in the central plutonium region to meet specific irradiation objectives. All of the plutonium assemblies contained Inconel 718 grids.

The twelve UO_2 assemblies consisted of five assemblies with the original Core I design (304 SS grids). Of these, one assembly (E-1) was a special 51-rod hollow UO_2 assembly designed to accommodate a supercritical test loop.

This assembly accumulated ~ 2100 MWD/tonne burnup during Saxton Core I operation. At the start of the plutonium program, it contained a stainless steel filler. The seven remaining UO_2 assemblies were of a new design (Inconel grids). These assemblies were located at the corners of the core to reduce the reactivity loss associated with the higher neutron cross section and the increased material volume of the new grid structure.

The special L-shaped assemblies (UO_2 fueled), used in Saxton Core I, and the original fuel bearing control rod followers (UO_2) were utilized in Saxton Core II.

The design of Saxton Core II is described in greater detail in References 1, 2, and 3 (below):

1. W. L. Orr, et. al., "Nuclear Design of the Saxton Partial Plutonium Core," EURAEC-1490, WCAP-3385-51, December 1965.
2. E. A. Bassler, et. al., "Mechanical, Thermal and Hydraulic Design of Saxton Partial Plutonium Core," EURAEC-1491, WCAP-3385-52, December 1965.
3. A. Biancheria, et. al., "Materials Design and Fabrication of the Saxton Partial Plutonium Core," EURAEC-1492, WCAP-3385-53, December 1965.

1.5 Comparison Between Measured and Calculated Values of Key Nuclear Parameters

A comparison between measured and calculated values of the moderator temperature coefficient, Rod 2 integral worth, the average burnup of the plutonium-bearing fuel, as well as the peak plutonium pellet burnup, is presented in Tables 1-1, 1-2, and 1-3. There is excellent agreement between the measured and predicted values for all of the above parameters, except for peak pellet burnup. The lack of agreement in the peak pellet burnup, however, is to be expected, since the analytical predictions were based on steady full power operation, with all rods out, for the initial core loading.

In practice, Core II was operated with Rod 2 in during the initial 800 hours of full power operation (23.5 MWt). This resulted in a lower than predicted peak pellet burnup, since the peak rod was in Assembly D-3, adjacent to control Rod 2.

It is important to note that Core II operated for 9,390 effective full power hours (EFPH) before shutdown. At shutdown, however, the moderator still contained an equivalent boron concentration of 150 ppm (normalized to a power level of 23.5 MWt and a moderator temperature of 530°F), which is equivalent to 860 EFPH. Thus, a total of 10250 EFPH of operation was available, compared to the predicted value of 9500 EFPH.

TABLE 1.1
CALCULATED VERSUS MEASURED MODERATOR TEMPERATURE COEFFICIENT
AS A FUNCTION OF BURNUP

<u>Core Average Burnup (MWD/MTM)</u>	<u>Moderator Temperature (°F)</u>	<u>Boron Concentration (ppm)</u>	<u>$\left(\frac{\delta\rho}{\delta T}\right)$ Calculation</u>	<u>$\left(\frac{\delta\rho}{\delta T}\right)$ Measurements</u>
0	530	2260	$- 2.22 \times 10^{-4}$	$- 2.36 \times 10^{-4}$
5715	515	1240	$- 2.56 \times 10^{-4}$	$- 2.61 \times 10^{-4}$
10196	530	620	$- 3.34 \times 10^{-4}$	$- 3.30 \times 10^{-4}$

TABLE 1.2

CALCULATED VERSUS MEASURED ROD 2 INTEGRAL WORTH
AS A FUNCTION OF BURNUP

<u>Core Average Burnup (MWd/MTM)</u>	<u>Calculated Worth (% $\Delta k/k$)</u>	<u>Measured Worth (% $\Delta k/k$)</u>
0	3.55	3.66
3716	3.38	3.40
5716	3.40	3.26
10490	3.25	3.30

TABLE 1.3

CALCULATED VERSUS MEASURED PLUTONIUM
AVERAGE AND PEAK PELLET BURNUPS AT EOL

	<u>Calculated Burnup (MWD/MTM)</u>	<u>Measured Burnup (MWD/MTM)</u>
PuO ₂ Region Average	15,925	15,440
PuO ₂ Peak Pellet	32,700	29,520

SECTION 2

CORE LOADING

During the core loading, twenty burned fuel assemblies in Core I were exchanged for twenty fresh-fuel assemblies. The fresh-fuel consisted of nine PuO_2 - UO_2 assemblies and eleven UO_2 assemblies. One burned assembly (E-1) from Core I, containing the superheat loop, was not exchanged. Of the nine PuO_2 - UO_2 assemblies, two contained vibratory compacted zirc-clad fuel, and the remaining seven assemblies contained pelletized zirc-clad fuel. Three of the nine PuO_2 - UO_2 assemblies contained some stainless steel clad rods dispersed among the Zircaloy-4 clad rods. Table 2.1 lists the exchanged assemblies, and date of loading. Figure 2.1 is a plan view of the fuel loading showing the positions of the different fuel types.

After each step in the loading sequence, the neutron multiplication was obtained by measuring count rates in the two source range channels and two special channels monitoring the startup sources. A plot of inverse multiplication ($1/M$) as a function of exchanged fuel for the "all rods in" configurations is shown in Figure 2-2. Detailed records were kept of $1/M$ for different rod configurations, step-by-step loading procedures, and count rate data at each step.

2.1 Initial Criticality

Core II startup testing was begun with the approach to, and establishment of, initial criticality of the reactor on December 6, 1965. Criticality was achieved by boron dilution with all control rods fully withdrawn from the core. Inverse multiplication was monitored as a function of time during boron dilution. Operational interruption of the boron dilution and the

TABLE 2.1

SAXTON CORE 2 FUEL LOADING

Plutonium Assembly - Serial #	Date Loaded	Fixed Fuel Rods	Removable Fuel Rods	Total Fuel Rods
D3-503-13-1	10-05-65	57 zirc* - pellets 2 SS - pellets 2 SS - vipac		61
C4-503-12-7	10-05-65	70 zirc - pellets	1 zirc - pellets	71
C2-503-12-2	10-07-65	70 zirc - pellets	2 zirc - pellets	72
E2-503-12-4	10-08-65	70 zirc - pellets	1 zirc - pellets	71
E4-503-12-8	10-11-65	70 zirc - pellets	2 zirc - pellets	72
C3-503-12-3	10-11-65	52 zirc - pellets 18 SS - pellets		70
D2-503-12-5	10-11-65	70 zirc - vipac	2 zirc - vipac	72
E3-503-12-6	10-12-65	70 zirc - pellets	1 zirc - pellets 1 source tube	71
D4-503-12-1	10-12-65	62 zirc - vipac 8 SS - vipac		70

*All zirc cladding is Zircaloy-4.

TABLE 2.1 (Cont)

SAXTON CORE 2 FUEL LOADING

Uranium Assembly - Serial #	Date Loaded	Fixed Fuel Rods	Removable Fuel Rods	Total Fuel Rods
F3-503-1-19	10-13-65	70 SS - pellets	1 SS - pellets	71
D5-503-1-10	10-13-65	70 SS - pellets	1 SS - pellets	71
B-503-2-3	10-13-65	61 SS - pellets		61
D1-503-1-7	10-13-65	70 SS - pellets	1 SS - pellets	71
F2-503-10-3	10-14-65	70 SS - pellets	2 SS - pellets	72
C5-503-11-2	10-14-65	61 SS - pellets		61
B4-503-10-4	10-14-65	70 SS - pellets	1 SS - pellets	71
E5-503-10-5	10-14-65	70 SS - pellets	2 SS - pellets	72
F4-503-1-11	10-15-65	61 SS - pellets		61
B2-503-10-2	10-15-65	70 SS - pellets	2 SS - pellets	72
C1-503-10-6	10-15-65	70 SS - pellets	1 SS - pellets	71
E1-503-7-1	Remaining From Core 1	49 SS - pellets		49

TABLE 2.1 (Cont)

SAXTON CORE 2 FUEL LOADING

Subassemblies				
Subassembly - Serial # - Core Location		Fixed Fuel Rods	Removable Fuel Rods	Total Fuel Rods
PuO ₂ -UO ₂	N1-503-4-26-D3	2 zirc - pellets 2 zirc - vipac	2 zirc - pellets 2 zirc - vipac	8
	N2 B3	Oscillator		
	UO ₂ N3-503-9-1-C5	3 SS - pellets 1 SS - vipac		4
	N4 E1	Supercritical Dummy		
UO ₂	N5-503-4-2-F4	9 SS - pellets		9

TABLE 2.1 (Cont)

SAXTON CORE 2 FUEL LOADING

Totals (Assemblies and Subassemblies)

	Pelletized (Zr) = 461 (fixed) + 9 (removable)	= 470
	Pelletized (SS) = 20 (fixed)	= 20
PuO ₂ -UO ₂	Vibratory compacted (Zr) = 134 (fixed) + 4 (removable)	= 138
	Vibratory compacted (SS) = 10 (fixed)	= 10
		<u>638</u>
	Pelletized (SS) = 804 (fixed) + 11 (removable)	= 815
UO ₂	Vibratory compacted (SS) = 1 (fixed)	= 1
		<u>816</u>

(Followers and "L" Sections)^Δ

	Six followers - pelletized (SS)	= 108
UO ₂	Nine "L" Sections - pelletized (SS)	= 81
		<u>189</u>

Grand Total = 1643 Fuel Rods

^ΔFuel from Core 1

Figure 2.1. Saxton Core II Fuel Configuration

Figure 2.2. Saxton Core II: Inverse Multiplication ($\frac{1}{M}$) versus Number of Fuel Assemblies Exchange

relatively large time constant associated with fluid circulation and mixing in the low pressure surge tank and reactor coolant system obscured, in part, the relation of inverse multiplication with estimated boron concentration in the core. The inverse multiplication data obtained, however, was entirely adequate for regulating demineralized water injection and for determining the point of criticality.

During the dilution, flow rates and tank levels were periodically monitored. These data were used, subsequently, in constructing a time-dependent boron balance in the fluid system and in generating the calculated reactor coolant boron concentration history (shown in Figure 2.3). The calculated history shows good agreement with the measured boron concentrations taken from periodic reactor coolant samples. Part of the discrepancy between the boron concentrations obtained by sampling and those calculated is attributed to the transit time in the sampling time from the pressure vessel to the sample collection point. The time corresponding to each sample is the time of collection, not the time of departure from the reactor. Another part of the discrepancy may well be the result of incorporating a low pressurizer spray flow rate in generating the boron balance. The absolute value of the spray flow rate is now well known.

Correlation of the time-dependent change in inverse multiplication with the time-dependent change in (calculated) boron concentration in the core yields the plot of inverse multiplication as a function of boron concentration (shown in Figure 2.4). The near linearity of the dependence of inverse multiplication on boron concentration is indicative of the close control which can be maintained over an approach to criticality by boron dilution, provided a reliable indication of change in reactor coolant boron concentration is available. The perturbations in the $1/M$ plot near criticality are due, primarily, to small errors in the calculated boron concentration resulting from interruptions in dilution rate.

Figure 2.3. Saxton Core II Calculated Boron Concentration History Approach to Initial Criticality

Figure 2.4. Saxton Core II Inverse Multiplication Plot Approach to Initial Criticality

SECTION 3

REACTIVITY KINETICS, COEFFICIENTS AND ROD WORTHS

At the beginning of core life and periodically throughout core life, measurements were made to determine control rod worths, boron worths, and moderator temperature coefficients. These measurements were made to determine the adequacy of design calculations and to obtain data which could be used to improve calculational techniques as well as to provide the reactor operator with the nuclear data necessary for the safe operation of the plant.

3.1 Zero Power Beginning-of-Life Measurements at Ambient Temperature

Immediately following initial criticality (hot) on December 6, 1965, zero power testing began. Boron endpoint measurements for all rods out, rod 2 in, rods 2 and 5 in, and rods 2 and 5 in, with rods 1 and 6 partially inserted, were made with the reactor at cold conditions. Table 3.1 shows the measured boron endpoints along with some pre-startup analytical predictions of endpoint borons. Experimental and analytical boron worths calculated from these endpoints and the integral rod worths are also included in the table.

3.2 Control Rod Worth Measurements

Differential control rod worths were obtained during a continuous boron dilution by recording the amount of rod travel and reactivity change associated with the rod travel. Reactivity was measured by means of an on-line analog computer. Effective delayed neutron fractions required by the computer for each rod configuration are given in Table 3.2

TABLE 3.1

SUMMARY OF ENDPOINT MEASUREMENTS
Established During Cold Conditions (ppm)

Configuration	Core Average Temperature (F°)	Calculated Boron Concentration (ppm)	Measured Endpoint Boron Concentration (ppm)
All Rods out	135	2715	2718
Rods 1,3,4,5 & 6 out Rod 2 in	155	2245	2263
Rods 1,3,4 & 6 out Rods 2 & 5 in	155	1690	1742
Rods 3 & 4 out Rods 4 & 6 at 18.4 Rods 2 & 5 in	150	-	1516

TABLE 3.1 (Cont)

DIFFERENTIAL BORON WORTHS

Control Rod Configuration	Calculated Boron Equivalent (ppm)	Boron Equivalent (ppm)	Measured Integrated Control Rod Worth ($\% \Delta \rho$)	Calculated Inverse Boron Worth (ppm/%)	Measured Inverse Boron Worth (ppm/%)
Cold (150°F) Measurements					
All rods out Rod 2 in	470	450	2.866	148	158
Rod 2 & 5 in	555	526	3.163	132	166
Rods 2 & 5 in 1 & 6 at 18.4 in.		225	1.453	-	155

TABLE 3.2
CALCULATED EFFECTIVE DELAYED
NEUTRON FRACTIONS

<u>Control Rod Configuration</u>	<u>B_{eff}</u>
All Rods Out	0.0040730
Rod 2 Worth Experiment	0.0041950
Rod 2 in	0.0043171
Rod 5 Worth Experiment	0.0044391
Rod 2 and 5 in	0.0045611
Rod 1 and 6 Worth Experiment	0.0045611

Differential and integral worth curves for rods 1 and 6 over the upper portion of their travel (with rods 2 and 5 in), rod 5 (with rod 2 in), and rod 2 (with all other rods out) for the cold condition are given in Figures 3.1, 3.2 and 3.3, respectively. Each rod worth measurement was made by withdrawing and inserting the rod. No significant differences in worth were noted between withdrawal and insertion.

3.3 Moderator Temperature Coefficient Measurements

In addition to the above measurements, experimental determination of differential temperature coefficients at each of the end point boron concentrations in the cold (150°F) conditions are shown in Figure 3.4. Each plotted data point represents a single temperature of a few degrees about the reference temperature.

In general, the data points show the expected degree of consistency. It should be noted that to obtain boron concentrations the rods had to be inserted so that the trend of differential temperature coefficient with boron shown is really a trend of temperature coefficient with boron and rod insertion.

3.4 Cold-to-Hot Reactivity Defects

As part of the initial testing program, the reactivity defect associated with heatup/cooldown was measured at two boron concentrations. The results of analysis of data secured during cooldown at 2130 ppm and subsequent heatup

Figure 3.1. Saxton Core II Control Rods 1 and 6 Differential and Integral Worths (Beginning of Life, Cold, Zero Power)

Figure 3.2. Saxton Core II Control Rod 5 Differential and Integral Worths (Beginning of Life, Cold, Zero Power)

Figure 3.3. Saxton Core II Control Rod 2 Differential and Integral Worths (Beginning of Life, Cold, Zero Power)

Figure 3.4. Saxton Core II Moderator Temperature Coefficient
 (Beginning of Life, 150°F, Zero Power)

at 1700 ppm are shown in Figure 3.5 and Figure 3.6, respectively. In both cases, the experimental data was erratic. The cooldown data was reasonably consistent down to a temperature of about 300°F, at which point, makeup water was injected into the primary system and that supplied as makeup disrupted reactivity. The correlation of temperature with reactivity and subsequent data were lost. During the heatup, the reactivity values generated by the reactivity computer proved to be singularly poor; differential control rod worths derived from the data have little relationship to corresponding rod worths obtained at hot or cold conditions. Consequently, the reactivity data was discarded and the change in reactivity corresponding to change in temperature during heatup was deduced from observed changes in control rod position and interpolation between hot and cold differential control rod worth values secured at constant temperature.

A close examination of the statepoint measurements in the hot and cold condition shows that the integrated reactivity defect in Figure 3.5 and Figure 3.6 is significantly larger than that obtained from statepoint differences and boron worths. This seeming inconsistency is a result of the method of making the measurement and not of any inherent error in either set. The measurements during the heatup and cooldown are made by moving control rods to maintain the reactor critical. This insertion of control rods during the cooldown would make the temperature coefficient more negative and the integrated defect larger. To attain a critical state with rod 2 inserted in the hot condition, the heatup must have been started with more rod inserted, and this would cause the differential coefficient to be more negative and the integrated defect larger.

After the core had accumulated 8475 MWD/MTM burnup, the reactivity defect on heatup again was measured using the same method as before. This measurement was made only between 280°F and 500°F and at 798 ppm boron. The results are shown in Figure 3.7.

3.5 Zero Power Reactivity Measurements at Operating Temperature

At the beginning of core life and periodically throughout the cycle,

Figure 3.5. Saxton Core II Differential Moderator Cooldown Coefficient and Cooldown Reactivity Defect (Beginning of Life, 2130 ppm Boron)

Figure 3.6. Saxton Core II Differential Moderator Heatup Coefficient and Heatup Reactivity Defect Beginning of Life 1700 ppm Boron

Figure 3.7. Saxton Core II Differential Moderator Heatup Coefficient and Heatup Reactivity
Defect 5475 MWD/MTM 798 PPM Boron

measurements were made of the all-rods-out and rod 2 inserted boron concentrations, the worth of control rod 2, the differential boron worth, the differential moderator temperature coefficient, and the xenon worth.

3.5.1 Boron Endpoints and Boron Worths

The just-critical boron concentration was determined in the all-rods-out configuration and the rod 2 inserted configuration at beginning-of-life (BOL), 3716 MWD/MTM, 5715 MWD/MTM and 10,490 MWD/MTM.

The data is given in Table 3.3. At beginning-of-life (BOL), measurements of the rod 2 and rod 5 in endpoint boron concentration, and the analytical prediction of the endpoint borons, were available for the BOL condition. They are presented in Table 3.3 for comparison. In general, the agreement between the calculated and the measured values is good. Differential boron worths calculated from the boron endpoints and the integral control rod worths given in the following section are presented in Table 3.4. Again at BOL, calculated values are presented for comparison. Though the BOL measurements failed to show the expected trend of boron worth with boron concentration, subsequent measurements do show a trend. This trend to higher boron worth is due to lower boron concentration and a shift in core power to the uranium with higher burnup. The end-of-life differential boron worth seems to be singularly high, but no convincing reason has been found to invalidate the measurement.

3.5.2 Control Rod Worth Measurements

The direct differential worth of a control rod was measured during continuous boron dilution or insertion by moving the rod to be measured in a series of steps and recording the amount of travel and change in reactivity associated with each step. The analog computer again was used for measuring reactivity. The different delayed neutron fractions used by the computer are listed in Table 3.5. Calculations made at 3716 MWD/MTM to determine the change in B_{eff} with burnup show only a 0.34 percent difference. Subsequent to this, no additional calculations of B_{eff} were made.

TABLE 3.3

SUMMARY OF ENDPOINT MEASUREMENTS
AT HOT ZERO POWER CONDITIONS

Control Rod Configuration	Burnup (MWD/MTM)	Core Average Temperature (°F)	Calculated Boron Concentration (ppm)	Endpoint Boron Concentration (ppm)
All rods out	BOL	530	2240	2296
Rods 1,3,4,5 & 6 out Rod 2 in	BOL	530	1600	1702
Rods 1,3,4 & 6 out Rods 2 & 5	BOL	530	925	1047
All rods out	3716	530	-	1565
Rod 2 inserted All others out	3716	530	-	1037
All rods out	5715	530	-	1266
Rod 2 inserted All others out	5715	530	-	795
All rods out	10,490	530	-	683
Rod 2 inserted All others out	10,490	530	-	312

TABLE 3.4

DIFFERENTIAL BORON WORTHS

Control Rod	Core Burnup (MWD/MTM)	Integrated Control Rod Worth ($\% \Delta \rho$)	Measured Boron Equivalent (ppm)	Calculated Boron Equivalent	Measured Inverse Boron Worth (ppm/%)	Calculated Inverse Boron Worth (ppm/%)
Rod 2 worth	BOL	3.69	594	640	161	178
Rod 5 worth (2 in)	BOL	4.03	655	675	162	152
Rod 2 worth	3716	3.30	528	-	160	-
Rod 2 worth	5715	3.26	491	-	151	-
Rod 2 worth	10,490	3.20	371			

TABLE 3.5

CALCULATED B_{eff} 's (AT 3716 MWD/MTM)

<u>Control Rod Configuration</u>	<u>B_{eff}</u>
All Rods Out	0.0044957
Rod 2 Moving	0.0045817
Rod 2 in	0.0046677
Rod 5 Moving	0.0047536
Rod 2 and 5 in	0.0048395

Differential and integral worth curves for rod 2 (all others out) and rod 5 (with 2 inserted) are shown in Figure 3.8 and Figure 3.9. The differential worth of rod 2 after 5715 MWD/MTM is shown in Figure 3.10. After the initial flattening from BOL there is very little change in the worth of rod 2.

The integral worths for 5715 MWD/MTM are given in Figure 3.11. The end-of-life (10,490 MWD/MTM) differential and integral worth of control rod 2 are shown in Figure 3.12. Again there is no change in the differential or integral worth.

The following tabulation shows the boron equivalent worth, the reactivity worth, and the calculated reactivity worth of control rod 2 as a function of burnup.

TABLE 3.6

ROD 2 EQUIVALENT REACTIVITY WORTHS

<u>Burnup (MWD/MTM)</u>	<u>Boron Equivalent (ppm)</u>	<u>Reactivity Worth ($\% \Delta \rho$)</u>	<u>Calculated Worth ($\% \Delta \rho$)</u>
0	594	3.66	3.55
3716	528	3.40	3.38
5716	491	3.26	3.40
10,490	371	3.30	3.25

Figure 3.8. Saxton Core II Control Rod 2 Differential and Integral Worths (Beginning of Life, Hot, Zero Power)

Figure 3.9 Saxton Core II Control Rod 5 Differential and Integral Worths (Beginning of Life, Hot, Zero Power)

Figure 3.10. Saxton Core II Control Rod #2 Differential Worth (5715 MWD/MIM Burnup, Hot, Zero Power, Rods 1, 3, 4, 5 and 6 at 40°)

Figure 3.11. Saxton Core II Control Rod #2 Integral Worth

Figure 3.12. Saxton Core II Differential and Integral Worths of Rod 2 (10590 MWD/MIM Burnup, Hot, Zero Power, Rods 1, 3, 4, 5 and 6 at 40")

The agreement between calculated and measured reactivity worth of the rod is considered excellent.

3.5.3 Moderator Temperature Coefficient

The data from the hot zero power beginning-of-life (BOL) moderator temperature coefficient measurements is given in Figure 3.13. The moderator temperature coefficient at various burnups and boron concentrations is shown in Figure 3.14. The exact trend of the differential coefficient is difficult to decipher because of the interaction of control rods, burnup, and boron on the measurements.

The differential moderator temperature coefficients were measured during continuous heatup and cooldown by observing at one minute intervals moderator average temperature (measured with RTD's and a Mueller bridge) and change in core reactivity. The reactor was maintained nearly critical during temperature change by compensating with control rod movement. Change in core reactivity due to change in temperature at each time point was given by the algebraic sum of actual core deviation from criticality as given by the computer at that time point plus the accumulated change in reactivity compensated for by periodic steps of rod motion up to that point. Correlation of temperature change in time and reactivity change in time yielded the differential coefficient.

In addition to those moderator temperature coefficient measurements at different boron and burnups, a series of temperature coefficient measurements were made at different temperatures. The measurements were made with the following core conditions: zero power, 800 ppm boron, all rods out, core average burnup of 8470 MWD/MTM. The data are shown in Figure 3.15.

3.5.4 Pressure Coefficient Measurements

Measurements of differential pressure coefficient were made during heatup and again at 530°F, both times in connection with differential temperature coefficient measurements made under closely similar conditions. Since the nuclear mechanisms underlying the pressure and temperature coefficients are similar, a scheme developed during Core I startup was used to evaluate

Figure 3.13. Saxton Core II Moderator Temperature Coefficient (Beginning of Life, 530°F, Zero Power)

Figure 3.14. Saxton Core II Moderator Temperature Coefficients versus Boron Concentration at 3716, 5715 and 10490 MWD/MTM Burnup; Hot, Zero Power

Figure 3.15. Saxton Core II Moderator Temperature Coefficient versus Temperature

the Core II results. Figure 3.16 is a plot of differential pressure coefficient versus differential temperature coefficient, showing the Core II data points superimposed on the Core I correlation. The close agreement between Core I and Core II results is indicative of the fact that both temperature and pressure coefficients rely on water density changes and that the interrelation between the two is little affected by fuel characteristics. Figure 3.17 is a recommended differential pressure versus boron concentration curve.

3.5.5 Xenon Reactivity Worth

A 72-hour xenon decay measurement following shutdown from equilibrium 21.5 MWt conditions was carried out as part of the Elevated Power Test Program at BOL. However, since the conditions of measurement were those of zero power, the results are reported here. Figure 3.18 shows the time dependent reactivity defect attributed to xenon as a function of time after power decrease from 21.5 MWt. The xenon transient shows consistently lower worth and relatively less peaking after shutdown than did corresponding data taken during the life of the all-uranium Core I. The differences are attributed to the increased core absorption cross section and to the lower average flux level prevalent in Core II as compared to Core I.

Figure 3.19 shows the gradual establishment of pure xenon decay with a half life of 9.1 hours at the later stages of the transient. The semi-log plot indicates that the xenon transient can be successfully extrapolated and the xenon defect closely estimated by about 50 hours after shutdown.

Values of differential control rod worth deduced from control rod motion and reactivity data secured during the xenon follow are compared to the recommended operational curve in Figure 3.20. There is no clear indication within the relatively broad band of experimental uncertainty of dependence of control rod differential worth on xenon concentration.

Figure 3.16. Correlation of Differential Pressure and Temperature Coefficients at Startup of Saxton Cores I and II

Figure 3.17. Recommended Differential Pressure Coefficient For Saxton Core II Beginning of Life

Figure 3.18. Saxton Core II Transient Xenon Defect After Shutdown From 21.5 MWt, Beginning of Life (Boron Concentration 1130 ppm, Zero Power, 530°F)

Figure 3.19. Saxton Core II Semi-Log Plot of Transient Xenon Defect After Shutdown From 21.5 MWt (Beginning of Life)

Figure 3.20. Saxton Core II Measured Differential Worths of Control Rod 5 During Xenon Follow

At 5715 MWD/MTM, a measurement of the reactivity defect associated with xenon build-in was made using a substitution technique. A baseline was established immediately after startup, and all the measurements were calculated from this temperature and rod position. The poison build-in with the control rods fixed and power level constant was necessarily compensated for by a decrease in moderator average temperature (ΔT). When the predetermined minimum temperature was reached, the rod was withdrawn (ΔH) quickly and temperature was restored to the initial value. The resultant poison magnitude was calculated from summing the ΔT 's and multiplying the sum by the average temperature coefficient to obtain its reactivity equivalent. A second calculation involving the ΔH measurement also involved two boron dilutions. The ΔH from each rod movement was multiplied by the appropriate average differential rod worth measured at zero power, and each boron dilution (ΔB) was multiplied by the average boron worth coefficient. These two reactivity values were then added to obtain their reactivity equivalent.

The temperature/xenon exchange and the control rod and boron/xenon exchange data is compiled in Table 3.7 and shown in Figure 3.21. The increase in xenon worth from the BOL measurement can be directly attributed to the increased power level to which the measurement was made.

3.5.6 Minimum Shutdown Reactivity Measurements

Determinations of minimum shutdown boron concentrations and control rod configurations adequate to give 2 percent shutdown with the maximum worth control rod fully withdrawn were made by means of control rod drops in both the cold and hot condition.

The measurements are described in Table 3.8. The first column gives the initial critical conditions; the second column gives the boron concentration for initial critical conditions. The third column gives the amount of shutdown reactivity after dropping the partially inserted rod. The fourth column gives the amount of boron to be added or removed to make the shutdown reactivity 2 percent. The fifth column is then the boron concentration for

TABLE 3.7

RESULTS OF THE XENON BUILD-IN MEASUREMENT AT 23.2 MW
AFTER 5715 MWD/MTM BURNUP IN SAXTON CORE II

Temperature/Xenon Exchanges		Rod and Boron/Xenon Exchanges	
Time From Startup (hrs)	Accumulated Reactivity (m ρ)	Time From Startup (hrs)	Accumulated Reactivity (m ρ)
0	0	0	0
2.60	3.01	1.00	3.54
5.50	3.28	4.00	3.38
9.40	3.75	7.00	3.60
12.43	2.60	10.50	2.26
16.40	2.93	14.00	2.46
22.70	3.02	18.00	3.54
39.00	3.01	28.00	2.91
49.00	0.45	49.00	1.30
Total = 22.05		Total = 22.99

Figure 3.21. Saxton Core II 5715 MWD/MTF Xenon Buildin Curve at
23.2 MWt, 510°F

TABLE 3.8

MINIMUM SHUTDOWN REACTIVITY MEASUREMENTS

Rod Configuration Before Rod Drop	Critical Boron Concentration (ppm)	Shutdown ρ After Rod Drop (mp)	Boron Equivalent of Surplus Shutdown (ppm)	Minimum Shutdown Boron Concentration (ppm)	Minimum Shutdown Rod Configuration
Cold Measurement Rod 2 at 40" Rod 4 at 26.14" Rods 1,3,5 and 6 at 0"	1516	-9.8	+163	1679	27.3" on 1 and 6
Hot Measurement Rod 2 at 40" Rod 5 at 38.46" Rod 1,3,4 and 6 at 0"	1040	-29.8 on xy Plotter -26.5 on L and N Recorder	-157 -104	883 936	19.5" on 1 and 6 22.7" on 1 and 6

2 percent shutdown. The last column gives the rod configuration that insures 2 percent shutdown at beginning-of-life if the rods are withdrawn from the all inserted configuration in a normal withdrawal sequence. For example, in the cold configuration, the reactor is 2 percent shutdown if it does not go critical with rods 1 and 6 withdrawn to 27.3" after rods 3 and 4 are completely removed (rods 2 and 5 in.). Normal control rod withdrawal sequence is: (1) rods 3 and 4 as a bank, (2) rods 1 and 6 as a bank, (3) rod 5 and (4) rod 2.

3.6 Reactivity Measurements at Power

3.6.1' Rod Worth Measurements

Upon completion of the BOL zero power testing, elevated power testing began. Rod worths were measured at 17 MWt in the same manner as the zero power rod worth measurements described in Section 3.2.2. Differential and integral rod worth curves are given for rod 2 (with all other rods withdrawn) and rod 5 (with rod 2 inserted) in Figures 3.22 and 3.23, respectively. Both worth curves are the result of a single measurement with data taken during rod 2 withdrawal (boron addition) and for rod 5 insertion (boron dilution). Delayed neutron characteristics used in the reactivity computer are listed below (Table 3.9).

TABLE 3.9

B_{eff} FOR SEVERAL CONTROL ROD CONFIGURATIONS

All rods out	0.0045212
Rod 2 moving	0.0046072
Rod 2 in	0.0046932
Rod 5 moving	0.0047791
Rod 2 and 5 in	0.0048650

Figure 3.22. Saxton Core II Control Rod 2 - Differential and Integral Worths (Hot, at Power)

Figure 3.23. Saxton Core II Control Rod 5 - Differential and Integral Worths (Rod 2 at 0" - Hot at Power)

3.6.2 Differential Boron Worth Measurements

Boron worth data were accumulated while gathering rod worth measurements by concurrently taking boron samples. The resulting differential boron worths are plotted versus boron concentrations in Figure 3.24. There is a great deal of scatter in the data, but some trend toward higher worth while decreasing boron is shown. In addition to the above measurements at beginning-of-life, (BOL) a series of substitution measurements were made at 3716 MWD/MTM in which boron worths were determined from rod/boron and boron/temperature interchanger. Though these are in a different boron range, they agree well with the assumed best line extrapolated from the BOL data.

3.6.3 Power Coefficient Measurements

During power operations, numerous measurements of the power coefficient were made at different power levels. Measurements relating the power defect to computer measured reactivity were carried out over the entire power range up to ~ 20 MW. The results of these measurements are shown in Figure 3.25. The only power coefficient measurement made subsequent to this was at end-of-life (10,490 MWD/MIM). On the figure, this measurement is shown to be less negative than the equivalent BOL measurement. This is thought to be because of the higher fuel temperatures predicted by thermal models for higher burnup.

3.6.4 Moderator Temperature Coefficient Measurements

The most extensive set of moderator temperature coefficient measurements were made during the substitution measurements at 5200 MWD/MTM. These values were inferred from temperature/rod and temperature/boron exchanges and previously measured rod worths. The extrapolation of the measurement agrees well with other temperature coefficient measurements done with the reactivity computer at higher and lower boron. The data for the above measurements is given in Figure 3.26, with a proposed straight line through the data points.

The results of the substitutional tests using small boron dilutions have shown that reliable data, consistent internally over a range of interrelated measurements and externally in terms of best values derived from other sources, can be obtained. The reactivity data necessary for operation of the plant

Figure 3.24. Sax Core II Differential Boron Worth versus Boron Concentration.

Figure 3.25. Saxton Core II Power Coefficient

Figure 3.26. Moderator Temperature Coefficient versus Boron
(Rod 2 Moving 30-18 Inches)

can be secured with relatively little effort and virtually no interference with normal reactor operation at full power. These measurements have proven to be some of the most reliable and informative measurements made during Core II.

3.6.5 pH Reactivity Effect

On numerous occasions during Core II life, the reactivity effect associated with a change in the main coolant pH was measured. This was done at power by compensating any reactivity change with moderator temperature and converting it to a reactivity by use of the appropriate temperature coefficient. The data from the pH measurements is tabulated in Table 3.10 and the pH reactivity coefficient versus hot pH is given in Figure 3.27. A measurement in which the main coolant pH was changed at zero power showed no measureable change in reactivity.

TABLE 3.10

SAXTON CORE II pH COEFFICIENTS

Date	pH Start	pH Finish	Δ pH Units	$\Delta\rho$ (mp)	$\Delta\rho/\Delta$ pH (mp/pH Unit)	pH Average
05-04-66	7.07	5.48	1.59	2.50	1.57	6.27
06-16-66	7.12	5.48	1.64	1.94	1.18	6.30
09-08-66	6.16	5.46	.70	1.23	1.76	5.81
11-29-67	5.61	7.32	1.71	1.31	0.77	6.47
12-08-67	7.32	5.61	1.71	1.13	0.66	6.47
12-14-67	5.60	7.40	1.80	1.16	0.64	6.50
02-05-68	5.57	7.38	1.81	1.83	1.01	6.48
02-09-68	7.40	5.60	1.80	1.55	0.86	6.50

Figure 3.27. Saxton Core II pH Coefficient

SECTION 4

CORE DEPLETION ANALYSIS

A significant portion of Saxton plutonium follow effort was devoted to continuous evaluation of the depletion characteristics of Core II. The effort entailed both an experimental evaluation of depletion and burnup and a continuous review and evaluation of the analytical methods used in predicting power and critical boron.

4.1 Experimental Core Burnup Follow

Core depletion is conveniently expressed in terms of the all rods out critical boron concentration as a function of operation. A running plot of the main coolant boron concentration versus burnup was maintained during Saxton Core II. This plot of boron concentration at reference conditions of 23.5 MWt, 510°F, and all control rods withdrawn is given in Figure 4.1. The assembly average burnup for the core at 4188 MWD/MTM and end-of-life (10,590 MWD/MTM) determined from PDQ-3 nuclear constants and measurements are presented Tables 4.1 and 4.2.

4.2 Analytic Core Burnup Follow

Throughout Core II life, the analytical nuclear parameters necessary in making incore power distribution measurements were generated using the LEOPARD-BUBBLE-PDQ-3 sequence. These calculations were made periodically to take into account the effect of burnup on power distribution. The calculations were made after experimental results were available from power operation and the power history of each fuel assembly was known from flux wire measurements. The measured irradiation history was used to determine group constants in the BUBBLE code by interpolation from a previously established boron concentration-irradiation matrix. These constants were then used in PDQ calculations in x-y geometry.

Figure 4.1. Comparison of Calculated and Measured Critical Boron Concentration as a Function of Burnup (Saxton Core II)

TABLE 4.1

DEPLETION AFTER 4188 MWD/MTM CORE OPERATION

Core Location	Assembly	Number of Rods	Initial MTM	MWD/MTM
1C	503-10-6	80	.0426	2504
1D	503-1-7	71	.03781	3059
1E*	503-7-1	58	.03089	2606
2B	503-10-2	72	.03834	2439
2C	503-12-2	72	.03469	5113
2D	503-12-5	72	.03396	6631
2E	503-12-4	80	.03854	5572
2F	503-10-3	81	.04313	2486
3B	503-2-3	70	.03728	3212
3C	503-12-3	70	.03471	6758
3D	503-13-1	61	.02948	7929
3E	503-12-6	71	.03421	6766
3F	503-1-19	71	.03781	3074
4B	503-10-4	80	.04260	2731
4C	503-12-7	71	.03421	5464
4D	503-12-1	70	.03353	6840
4E	503-12-8	72	.03469	5307
4F	503-1-11	70	.03728	2739
5C	503-11-2	70	.03728	2846
5D	503-1-10	80	.0426	3366
5E	503-10-5	72	.03834	2437
Followers				
1*	505-2	18	.009216	4074
2*		18	.009216	4835
3*	505-3	18	.009216	4297
4*	505-4	18	.009216	4244
5*		18	.009216	5428
6*	505-5	18	.009216	4540

*Burnup not including Saxton Core I Burnup

TABLE 4.2

DEPLETION AFTER 10590 MWD/MTM CORE OPERATION

Core Location	Assembly	Number of Rods	Initial MTM	MWD/MTM
1C	503-10-6	80	.0426	6666
1D	503-1-7	71	.03781	7710
1E*	503-7-1	58	.03089	6767
2B	503-10-2	72	.03834	6470
2C	503-12-2	72	.03469	12911
2D	503-12-5	72	.03396	16052
2E	503-12-4	80	.03854	13492
2F	503-10-3	81	.04313	6592
3B	503-2-3	70	.03728	8247
3C	503-12-3	70	.03471	15909
3D	503-13-1	61	.02948	19704
3E	503-12-6	71	.03421	16292
3F	503-1-19	71	.03781	8165
4B	503-10-4	80	.04260	7037
4C	503-12-7	71	.03421	14259
4D	503-12-1	70	.03353	16792
4E	503-12-8	72	.03469	13631
4F	503-1-11	70	.03728	7289
5C	503-11-2	70	.03728	7934
5D	503-1-10	80	.0426	9342
5E	503-10-5	72	.03834	6901
Followers				
1*	505-2	18	.009327	10115
2*		18	.009327	7998
3*	505-3	18	.009327	10798
4*	505-4	18	.009327	10220
5*		18	.009327	13790
6*	505-5	18	.009327	11268

*Burnup not including Saxton Core I Burnup

The agreement between measured and calculation in general, was good (see Section 5.0). However, as shown in Figure 4.2, at approximately 5000 EFPH, just critical boron predictions using this method start to deviate from measurements.

Because of this, a study was made to determine possible discrepancies in the analysis. Those identified were: failure to include the effects of non-uniform axial depletion in PDQ-xy calculations; and differences in plutonium fission product cross sections from those included in LEOPARD and, thus, inherently incorporated in the BUBBLE-PDQ03 analysis sequence. Moreover, due to the average assembly representation in the BUBBLE-PDQ03, it is impossible to determine local burnup and power effects correctly. In LEOPARD, all fission products except Xe-135 and Sm-149 are lumped together and treated as a single nuclide whose number density equals the integrated fission density. The cross sections σ_{a3} and σ_{a4} (which are for the resonance and thermal spectrum, respectively), used for lumped fission products, vary with burnup and are represented in LEOPARD by polynomials which are fitted to the results of a CINDER calculation for a 3 w/o U-235 enrichment and a water/U ratio of 3.0. This treatment is inadequate for plutonium-fueled cores because of the difference in fission product yields between uranium and plutonium fissions and the different neutron flux levels.

To investigate the effect of the LEOPARD representation on the analyses, CINDER calculations were carried out for the 6.6 w/o PuO_2 - UO_2 and the 5.7 w/o UO_2 fuels at the Saxton pitch. The lumped fission product cross sections for the uranium fuel are shown in Figures 4.3 and 4.4. As shown in these figures, the change in enrichment and W/U compensate, so that there is little difference from the LEOPARD-calculated cross sections for the uranium region. The lumped fission products cross sections for the plutonium fuel as calculated in CINDER are shown in Figures 4.5 and 4.6. Use of the CINDER fission products cross sections in place of the LEOPARD fission products cross section would reduce the PDQ-3 calculated life by approximately 250 hours. Since the effects of non-uniform axial depletion are not considered in the two dimensional calculations, a correction for the reactivity difference between uniform and non-uniform axial depletion of the core is applied.

Figure 4.2. A Comparison of the Calculated and Measured Critical Boron Concentration as a Function of Hours Operation for Saxton Core II

Figure 4-3. Comparison of 5.7% Enriched UO_2 Resonance Fission Product Cross Section from CINDER with Fit from LEOPARD

Figure 4-4. Comparison of 5.7% Enriched UO_2 Thermal Fission Product Cross Section from CINDER with Fit from LEOPARD

Figure 4-5. Comparison of PuO₂ Resonance Fission Product Cross Section from CINDER with Fit from LEOPARD

Figure 4-6. Comparison of PuO_2 Thermal Fission Product Cross Section from CINDER with Fit from LEOPARD

The axial depletion was determined with the aid of a one-dimensional calculation which considers pointwise effects of burnup, water density, and xenon. The reactivity difference determined for the PuO_2 - UO_2 and the UO_2 fuels is shown in Figure 4.7.

In addition to the above items, a revised diffusion theory depletion analysis that would follow local burnup and power effects more accurately was performed.

The revised analysis was carried out with a LEOPARD-PDQ-7-HARMONY sequence. In this sequence, the diffusion theory group constants were generated using improved plutonium yields for iodine, xenon, samarium and promethium. The required LEOPARD calculations were made using the actual operating conditions of the core which included a slightly lower moderator temperature than that specified in the original design operating conditions. New fuel temperatures for the PuO_2 - UO_2 were generated with the latest thermal calculation models. A new homogenization method to represent the control rod followers was adopted. A bias of 0.9% ΔK_{eff} , determined from the Saxton plutonium criticals, was used in the 6.6 w/o PuO_2 - UO_2 fuel. No bias was used for the 5.7 w/o UO_2 fuel.

In the PDQ-7-HARMONY sequence, burnup-dependent macroscopic diffusion theory group constants were input in the form of a burnup matrix. Power and accumulated burnup is computed at each point. The burnup at each point is then used to find new group constants from the burnup matrix. The boron concentration was changed separately.

Table 4.3 shows the time step sequences used in the depletion calculation. At the end of each time step, certain subassembly changes were made in the removable positions in locations P-3, F-4, and C-5. These were included explicitly in the calculations.

The calculated just-critical boron values are compared with measured values in Table 4.4. Subassembly changes made after the original calculations made it necessary to recompute the final two time steps. Step VII (a) represents a calculation corresponding to the core condition before the subassembly changes with Step VII (b) corresponding to the core condition after the change. The calculated effect on the critical boron requirement for the change was +56 ppm,

Figure 4-7. Reactivity Difference Between Uniform and Non-Uniform Depletion - 6.6 w/o PuO_2 and 5.7 w/o UO_2 Fuel

TABLE 4.3

PDQ-7 ANALYSIS SEQUENCE AND CORE CHANGES
USED IN SAXTON CORE II DEPLETION STUDY

Time Step	Beginning Time (hrs)	Boron* (ppm)	Control Rod Position
I	125.0	1550	All Rods Out
II	125.0	1550	Rod #2 In
III	800.0	1350	All Rods Out
IV	1810.0	1125	All Rods Out
V	3640.0	750	All Rods Out
VI	5640.0	400	All Rods Out
VII (a)	7640.0	200	All Rods Out
VII (b)	7640.0	200	All Rods Out
VIII	9500.0	100	All Rods Out

*Used in calculation. Not necessarily equal to critical boron shown in Table 4.4.

TABLE 4.4

COMPARISON OF CALCULATED AND MEASURED CRITICAL BORON CONCENTRATIONS AS A
FUNCTION OF SAXTON CORE II OPERATION

Time Step	EFPH @ 23.5 MWt	MWD/MTM	Analysis	Measurement
I	125.0	146.0	1724	1743
III	800.0	937.0	1507	1530
IV	1810.0	2120.0	1294	1319
V	3640.0	4265.0	960	997
VI	5640.0	6607.0	624	692
VII (a)	7640.0	8950.0	356	414
VII (b)	7640.0	8950.0	412	414
VIII	9500.0	11060.0	202	-

(a) prior to subassembly change

(b) after subassembly change

which is equivalent to an increase in system reactivity of $\approx 0.4\%$. The data is shown on the boron versus burnup curve (Figure 4.1); the good agreement is clearly evident.

SECTION 5

POWER DISTRIBUTION MEASUREMENTS

At the beginning-of-life (BOL) and throughout the core life, numerous measurements were made of the power distribution in the reactor using the incore instrumentation. The flux maps were made at many different control rod positions and power levels with both flux wire and direct reading fission chambers.

The most extensive set of measurements were made at BOL. The maps at different rod positions were necessary to determine the adequacy of design calculations and to establish safe operating limits for the reactor. Hot channel factors and peak power levels, in kw/ft were obtained from an analysis of the flux map data and are given in Table 5.1. An engineering factor of 1.045 is included in values of F_Q and peak kw/ft. No uncertainty factors have been applied to any of the numbers in the table. The locations of the peak rods are shown in Figure 5.1.

Additional Flux maps, along with the previous measurements, were used to determine the trend of hot channel factor with control rod position. Three curves from those measurements are reported here. Figure 5.2 illustrates the variation of the axial hot channel factor (F_Z) as a function of control rod configuration for the three peak fuel rods. Figure 5.3 shows how the radial hot channel factor ($F_{\Delta H}^N$) varies with control rod position for the same three peak rods of Figure 5.2. The last figure, 5.4, shows how the total hot channel factor ($F_q^N = F_Z \times F_{\Delta H}^N$) varies with control rod position for various peak rods. None of the figures has engineering factors included in the hot channel numbers. The rod identifications in these figures correspond to the hot channel locations shown in Figure 5.1.

TABLE 5.1
HOT CHANNEL FACTORS (ROD 2 INSERTED)

Control Rod 5 Position (inches withdrawn)	Method of Measurement	Power Level During Measurement (MW)	F_Z	$F_{\Delta H}^N$	F_{Q^*}	Peak Power + (KW/FT)	Peak Rod Position
15.65	Wires	10	1.6654	1.8251	3.1770	15.153	103
15.65	DET	10	1.7568	1.9506	3.5811	17.080	103
18.48	DET	10.63	1.8130	1.5960	3.0238	14.408	90
21.55	Wires	17	1.6658	1.7147	2.9848	14.209	90
21.55	DET	16.9	1.6034	1.8629	3.1214	14.859	88
OUT	Wire	17.5	1.3108	2.2239	3.0463	14.435	82
OUT	DET	17.5	1.3566	2.0305	2.9494	13.973	85
28.55	Wires	17	1.4864	1.9553	3.0371	14.429	90
28.55	DET	16.6	1.5030	1.8916	2.9711	14.115	90
29.02	Wires	19.5	1.4411	1.9802	2.9320	14.163	90
29.02	DET	19.54	1.4776	1.9037	2.9395	13.961	90
30.00	DET	21.58	1.4505	1.9316	2.9279	13.901	90

TABLE 5.1 (Cont)

HOT CHANNEL FACTORS (ROD 2 INSERTED)

Control Rod 5 Position (inches withdrawn)	Method of Measurement	Power Level During Measurement (MW)	F_Z	$F_{\Delta H}^N$	F_{Q*}	Peak Power + (KW/FT)	Peak Rod Position
33.65	DET	21.2	1.3548	1.9465	2.7559	13.072	85
OUT	DET	21.5	1.3532	2.0764	2.9364	13.914	85
OUT	Wire	21.5	1.3088	2.0962	2.8670	13.586	82
IN	Wire	16.6	1.3110	1.9444	2.6638	12.764	37
17.2	Wires	17	1.6266	1.8507	3.1458	14.995	113
Rod 2 @ 26	Wires	16.67	1.3868	2.0546	2.9777	14.234	86

$$* F_Q = F_Z \times F_{\Delta H}^N \times 1.045$$

+ Includes engineering factor = 1.045, peak referenced to 23.5 MWt

Individual Fuel Rod Source Numbers for Saxton Core 2 Incorporates

57-113 Pu
114-138 U

Other Sources:

1-21 Assemblies
22-26 Subassemblies
27-32 Followers
33-34 L-Section in Pu
35-56 Below T/C

Figure 5.1. Saxton Core II Hot Channel Locations

Figure 5.2. Saxton Axial Peaking Factor

Figure 5.3. Saxton Nuclear Enthalpy Rise Peaking Factor

After approximately 5700 MWD/MTM ($\sim$ 5000 hours), additional flux map data were obtained. These measurements showed that the radial peaking factors, $F_{\Delta H}^N$, decreased about 6 percent from those at beginning of life. Figure 5.5 illustrates the change in axial hot channel factor, F_z , for several high power fuel rods as a function of control rod 2 position. Figure 5.6 shows the highest total hot channel factor, ($F_q^N = F_{\Delta H}^N \times F_z$) for various control rod positions as determined from measurements at 1000 hours and 5000 hours.

Figure 5.5. Saxton Axial Peaking Factors

Figure 5.6. Saxton Nuclear Heat Flux Peaking Factor