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SAXTON CORE II
FUEL PERFORMANCE EVALUATION
PART I: MATERIALS

by

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SECTION 1

INTRODUCTION

1.1 DESCRIPTION AND OBJECTIVES OF SAXTON PLUTONIUM PROGRAM

The Saxton Plutonium Project is part of an overall program to advance plutonium recycle technology in water reactor systems. It is conducted by the Westinghouse Electric Corporation in co-operation with the Saxton Nuclear Experimental Corporation (SNEC) under USAEC Contract AT(30-1)-3385. The contract is administered by the USAEC New York Operations Office for the Joint United States-Euratom Research and Development Board.

The project is an integrated recycle program which includes design, fabrication, reactor operation, and post-irradiation evaluation of a partial plutonium core. Irradiation was performed in the Saxton reactor, which is well-suited to commercial bulk engineering tests because it is highly instrumented, and core performance can be continuously evaluated.

The overall purpose of the Saxton Plutonium Project is to develop information concerning the utilization of plutonium-enriched fuel in pressurized water reactor (PWR) systems. More specifically, the objectives are to:

1. Perform pilot-scale tests of plutonium-enriched fuel in a water reactor environment.
2. Compare the performance of mixed-oxide fuel fabricated by two economically promising techniques, i.e., pelletized vs. vibrationally compacted (vipac).
3. Obtain nuclear data of interest to plutonium recycling, especially in depletion and generation of transuranic isotopes.
4. Provide a preliminary basis for the selection and design of plutonium fuel for a large PWR.

The project was initiated in early 1964, and core design and fabrication activities were completed with delivery of the core at the reactor site in October, 1965. Loading of the core and initial operation were accomplished by December, 1965, and full power operation began in January 1966.

Nine complete fuel assemblies (9 x 9 rod arrays) containing 6.6 w/o plutonium enriched fuel were inserted into the central region of the Saxton reactor. The central assembly contains a removable 3 x 3 subassembly constructed such that four of the fuel rods could be removed at exposure levels intermediate to those achieved at the end of core life. Several of the rods within the 9 x 9 array are individually removable for intermediate examination or replacement. Seven of the assemblies contain pelletized fuel, and two contain vibrationally-compacted fuel. Zircaloy-4 cladding was employed for the bulk of the fuel rods, with some Type 304 stainless steel cladding included for comparison. A schematic of the Saxton Core II loading plan is shown in Figure 1-1.

The fuel assemblies were designed and built by Westinghouse, while the individual fuel rods were fabricated to Westinghouse design by Nuclear Materials and Equipment Corporation (NUMEC) and the Battelle Northwest Laboratories under subcontract to Westinghouse.

1.2 SCOPE OF REPORT

This topical report covers the materials evaluation of irradiated fuel from the plutonium region of Saxton Core II. It briefly discusses the design, fabrication, and operating history of this core. The major emphasis in the report is the evaluation of fuel materials performance as determined by both non-destructive and destructive examinations after irradiation to a wide range of burnups. In addition, the report summarizes the inspection of selected rods from Core II prior to their reconstitution in seven new "loose lattice" assemblies to be irradiated as part of an extended burnup program in Core III. Another report, WCAP-3385-56 Part II, covers the evaluation of the mass spectrometric, radiochemical, and burnup data of the mixed-oxide from Saxton Core II.

	B	C	D	E	
1		U	U	U	
2	U	P	V	P	U
3	U	P	P	P	U
4	U	P	V	P	U
5		U	U	U	

LEGEND:U UO_2 PELLETSP $\text{PuO}_2\text{-UO}_2$ PELLETS,
MECHANICALLY MIXEDV $\text{PuO}_2\text{-UO}_2$ VIBRATIONALLY
COMPACTED

Figure 1-1. Plan View of Saxton Core Showing Fuel Assembly Locations

SECTION 2

DESIGN OF PLUTONIUM REGION OF SAXTON CORE II

2.1 NUCLEAR DESIGN

The nuclear design was conducted in three steps. Initially, parametric studies were carried out to determine the performance characteristics of the Saxton reactor containing a partial core of plutonium. Later, more specific nuclear design calculations were performed to set the enrichment and determine the available burnup for a core containing nine central plutonium fuel assemblies with 12 surrounding uranium assemblies. Finally, a series of critical experiments using the design fuel and a supporting program of analysis were used to confirm the specified nuclear design. Details of the nuclear design are described in Reference 1.

The Saxton Core II nuclear design predicted a lifetime capability of 9,300 MWD and an average burnup in the plutonium fuel of 15,350 megawatt days thermal per metric tonne heavy metal (MWD/MTM). The actual Core II lifetime was 9190 MWD.

The supporting critical experiment program^[2] provided significant beginning-of-life physics information about the fuel and formed the basis for improving the correlation of analysis with experiment for plutonium-fueled systems. Critical experiments with water-moderated, single-region and multi-region $\text{PuO}_2\text{-UO}_2$ fueled cores were performed in the CRX reactor critical facility at the Westinghouse Reactor Evaluation Center (WREC) at Waltz Mill, Pennsylvania. Close agreement was found between predicted and measured beginning-of-life nuclear characteristics.

2.2 MECHANICAL, THERMAL, AND HYDRAULIC DESIGN

The mechanical, thermal, and hydraulic design guidelines for the $\text{PuO}_2\text{-UO}_2$ portion of Saxton Core II included: 1) 20,000 MWD/metric ton peak rod average

burnup; 2) 16 kw/ft maximum design heat rating in the rods; 3) internal gas pressure at end-of-design life to be less than external reactor operating pressure; and 4) fuel rod outside diameter, length, and lattice spacing to be the same as for the UO_2 rods in Cores I and II. The details of this aspect of the program are reported in Reference 3.

In addition to the fuel rods, the basic components of each fuel assembly were four grids, two enclosure halves, and top and bottom nozzles. The grid assemblies are of brazed "egg crate" construction and are spaced axially on ten-inch centers to provide lateral support for the fuel rods. The enclosure halves are welded to the peripheral straps of the grid assemblies to support the grids and to tie the fuel assembly together. The nozzles, which provide a means of handling the fuel assemblies and of positioning the assemblies in the reactor core, are welded to the top and bottom ends of the enclosure halves. Figure 2-1 shows a typical as-fabricated fuel assembly.

The fuel rods are arranged in a 9 x 9 square lattice with a 0.580 inch pitch in a typical main fuel assembly. Of the possible 81 lattice locations in this pattern, nine locations at one outer corner are eliminated from each fuel assembly to provide room for cruciform control rods positioned between the assemblies. In addition, two lattice locations in each fuel assembly were left vacant during fabrication to allow for insertion of flux wire thimbles, source rods, or removable fuel rods when the assembly was installed in the reactor.

The individual rods are nominally 39.0 inches long, with an active fuel length of 36.6 inches. Rod outside diameter is 0.391 inches; clad thickness is 23 mils for the Zircaloy and 15 mils for the stainless steel clad.

2.3 MATERIALS DESIGN

Materials design entailed selection of the cladding and fuel rod fabrication techniques employed for the project, development of fuel specifications, and provision of materials information to other design groups for establishing design parameters and safety criteria. The details of the materials design are given in Reference 4.

Figure 2-1. Typical 9 x 9 Saxton Fuel Assembly

In selecting the fabrication processes for the oxide fuel, the following factors were considered:

1. In-pile reliability
2. Projected economics
3. State of development

Evaluation of the available evidence led to selection of vibrational compaction and pelletization of mechanically blended fuel. Fuel fabricated by both methods already had been tested in various short-term experiments. Testing of bulk quantities of vipac fuel in EBWR is reported elsewhere.^[5] Other fabrication methods, such as extrusion and swaging, were not considered sufficiently advanced for proof-testing in commercial reactors.

Zircaloy-4 cladding was used for the bulk of the plutonium-bearing fuel rods, because it was expected to be generally employed in future cores. Some Type 304 stainless steel cladding was included for comparison.

Table 2-1 summarizes the materials selection for the program. All fuel is natural UO_2 enriched to a nominal 6.6 w/o PuO_2 . The plutonium contained 8.6 at/o Pu-240. Table 2-2 summarizes the reactor operating conditions for the program.

TABLE 2-1

MATERIALS SELECTION

<u>Clad</u>	<u>Fuel Form</u>	<u>Fuel Preparation Method</u>	<u>Fuel Density % T.D.**</u>	<u>No. Rods Inserted In Reactor</u>
Zr-4	Pellets	Mechanical Mixing	94 $\pm$ 2	470
Zr-4	Vipac	Mech. Mixing-Nupac*	87 $\pm$ 1	138
304 SS	Pellets	Mechanical Mixing	94 $\pm$ 2	20
304 SS	Vipac	Mech. Mixing-Nupac*	87 $\pm$ 1	10

* Battelle Northwest Laboratories high energy impaction process.

** Percentage of Theoretical Density.

TABLE 2-2

SAXTON REACTOR DESIGN OPERATING CONDITIONS

Maximum Power Level	23.5 Mw(t)
Maximum Linear Power Density	16 kw/ft
Maximum Heat Flux	531,400 Btu/hr-ft ²
Average Coolant Temperature	277°C (530°F)
System Pressure	2,000 psia
Maximum Clad Surface Temperature	339°C (642°F)
Average Clad Temperature at Hot Spot (SS)	356°C (674°F)
Average Clad Temperature at Hot Spot (Zr-4)	367°C (692°F)
Maximum Fuel Central Temperature	2200°C (3992°F)
Peak Burnup	>25,000 MWD/MTM
Chemical Shim, Beginning of Life	2,000 ppm Boron
Initial Loading - PuO ₂ -UO ₂	345 Kg/9 assemblies
Initial Loading - UO ₂	525 Kg/12 assemblies

SECTION 3

SAXTON CORE II OPERATING EXPERIENCE

3.1 NUCLEAR OPERATIONS SURVEILLANCE

Operation of the partial plutonium core at full design power levels was completely satisfactory. A continuing program of nuclear operations analyses showed no significant deviation from expected core operating characteristics. These analyses included investigation, at power, of boron and control rod worths, temperature and power coefficients, core depletion rate, and core flux wire and detector maps. Core nuclear parameters were also evaluated in two series of limited zero-power tests performed at approximately one-third and two-thirds of the expected core life. These latter tests included measurements of boron and control rod worths, temperature and pressure coefficients, minimum shutdown reactivity, and xenon decay. The results of these tests are given in References 6 through 10.

3.2 SUMMARY OF IRRADIATION HISTORY OF PLUTONIUM FUEL

Initial power operation of Saxton Core II took place on December 20, 1965. After measurement of nuclear parameters and core peaking factors early in January, 1966, power was increased in steps to 21 megawatts, thermal (MWt) on January 8. Reactor physics measurements and flux mapping continued during the next month at power levels in the range of 17 MWt to 21 MWt. Power was increased to the licensed value of 23.5 MWt on February 7, 1966. Except for brief shutdowns for operator license examinations and additional nuclear measurements, the reactor operated at 23.5 MW until March 31, when it was shutdown for plant maintenance and for removal of the central 3 x 3 subassembly. At the time of removal, the fuel in the subassembly had achieved an average burnup of about 4500 MWD/MTM, with a peak of ~6100 MWD/MTM. Visual inspection of the subassembly with an underwater periscope showed that it was in

excellent mechanical condition, with very small amounts of crud on the fuel cladding. The four removable rods from the subassembly were later shipped to the Westinghouse Post-Irradiation Facility (WPIF) for detailed post-irradiation examination.

The reactor was returned to 23.5 MWt on April 26, 1966, and operated at this power level until February 1, 1967, except for two major outages. The reactor was shutdown from July 22 to August 23 for a vapor containment leak rate test and to change subassembly experiments. It was also shutdown from October 14 to November 21 for installation of an in-pile supercritical loop.

During the extended shutdown in 1967, five of the removable fuel rods in 9 x 9 assemblies were removed from the core and examined with a periscope and remote profilometer. They were then stored in the pool for use as reference rods in the subsequent overpower tests and replaced with spare rods. Four other removable rods, also from 9 x 9 assemblies, were similarly examined and then reinserted in the core, but in new locations. Examination of these nine rods revealed no unusual cladding deformation, wear, cracks, or other evidence of anomalous performance. Nuclear calculations were performed to ensure that no local power peaking problems would occur as a result of either replacing the five partially burned rods with fresh fuel rods or by repositioning the other four.

From August, 1967, to February, 1968, the reactor operated intermittently at full power (23 MWt), accumulating an additional 1150 effective full power hours during the period. In February, the reactor was shutdown for scheduled maintenance and movement of experiments. The reactor was then prepared for the power escalation program. Late in April, 1968, the reactor was taken to 23 MWt at a system pressure of 2200 psi. After flux mapping and determination of control rod positions, the power was escalated step-wise from 23 MWt to 31 MWt over a 20-day period in May. During the escalation, numerous flux maps were made to determine power distribution.

The reactor was maintained at zero power in June for inspection of and changes in experimental test assemblies, including the Overpower Test as well as for routine plant maintenance. The first step of the Overpower Test took place in early July, and the two test rods were measured with a profilometer and

returned to the core. During August, the second step of the Overpower Test was completed, with the reactor at ~25 MWt for seven days. The remaining phases of the Overpower Test were accomplished in September and October, with two additional overpower steps from reactor power levels of 22.6 MWt to ~26 MWt. The operating history of this overpower test is described in more detail in Section 4.3.3.

Core II operation terminated on October 18, 1968. At the end of core life, the total time at power was 9360 effective full power hours (EFPH). The corresponding core average burnup was 10,940 MWD/MTM, while the plutonium region had an average burnup of 17,400 MWD/MTM. Subsequent measurements and data reduction showed that the burnups of the peak plutonium rod were ~21,000 MWD/MTM (rod average) and ~28,000 MWD/MTM (peak pellet).^[11]

Table 3-1 summarizes the power history of Saxton Core II in terms of average reactor power for each major time step.

TABLE 3-1

SUMMARY OF SAXTON CORE II IRRADIATION HISTORY

<u>Time Step No.</u>	<u>No. of Days</u>	<u>Average Reactor Power, MWt</u>	<u>Time Step No.</u>	<u>No. of Days</u>	<u>Average Reactor Power, MWt</u>
1	5	6.3	28	207	0.0
2	10	17.4	29	2	15.2
3	1	0.0	30	2	0.0
4	20	18.4	31	6	19.3
5	21	21.5	32	16	0.0
6	2	0.0	33	3	6.8
7	5	12.4	34	1	0.0
8	31	22.3	35	5	10.0
9	24	0.0	36	20	0.0
10	6	20.0	37	10	21.4
11	31	23.4	38	19	21.0
12	4	20.1	39	41	0.0
13	2	0.0	40	2	5.9
14	21	21.3	41	12	22.1
15	3	0.0	42	42	0.0
16	22	22.2	43	5	14.0
17	31	0.0	44	30	25.2
18	9	22.2	45	31	0.0
19	30	23.4	46	10	19.9
20	14	22.3	47	28	0.0
21	18	0.0	48	3	14.1
22	10	18.9	49	1	0.0
23	12	0.0	50	11	21.9
24	8	21.5	51	10	0.0
25	11	24.2	52	21	23.1
26	31	23.4	53	21	0.0
27	1	10.1	54	4	18.0

Summary: (1) Total Energy Generated = 9190 megawatt-days
 (2) Total Operating Time = 433 days
 (3) Average Operating Power = 21.3 MWt
 (4) Total Shutdown Time = 533 days

SECTION 4

POST-IRRADIATION EXAMINATIONS AND ANALYSIS

4.1 GENERAL

The evaluation of Saxton Core II materials performance was accomplished in five phases:

1. Hot laboratory examination of four low burnup rods removed from the center subassembly in April, 1966.
2. Non-destructive examinations of nine removable fuel rods at the Saxton reactor site during the extended shutdown in 1967. Results of these examinations were summarized in Section 3-2.
3. Examination of two overpower test rods at Saxton and at the WPIF, and subsequent comparisons with two reference rods.
4. Major post-irradiation examinations at the WPIF Hot Laboratory of high burnup fuel rods irradiated throughout Core II.
5. Non-destructive inspection of selected rods from Core II prior to their insertion into reconstituted assemblies for extended irradiation in Core III.

The nature of the examinations, sampling plan (if applicable), and evaluation of results for each phase will be discussed in the following sections.

4.2 EXAMINATION OF LOW BURNUP FUEL

In addition to the major post-irradiation examination and evaluation of rods removed from the fuel assemblies at the end of core life, two pelletized fuel rods and two vibrationally-compacted fuel rods were removed from the central 3 x 3 subassembly in April 1966. These rods had accumulated average exposures of about 4500 MWD/MTM and peak exposures of about 6100 MWD/MTM.

Visual and dimensional examination of the removed fuel rods revealed no surface anomalies or evidence of significant wear or fretting at the area of contact between the support grid spring-clip fingers and the cladding tube. Diameter measurements obtained with a remote spiral trace profilometer showed no deviation from the original fabrication tolerances and no evidence of swelling, blisters, or clad ridging. Furthermore, there was no significant dimensional difference between the vipac and pellet rods. Details of the profilometer measurement were reported previously.^[8]

The four rods were punctured, and the contained gases were collected for mass spectrometer analyses to determine the volume of fission gases released from the $\text{PuO}_2\text{-UO}_2$ fuel. The results of the analyses are shown in Table 4-1. Rods of the same kind yielded similar gas samples and the Xe/Kr ratios were similar for all rods. Observed differences in the composition of the vibrationally-compacted fuel and pelletized rod gas samples can be partly explained by the different gas atmosphere used in welding the rods. (The initial atmosphere in the vipac rods was 100 percent helium, while that in the pellet rods was 10 percent argon-90 percent helium.) Further, the high nitrogen content of the vipac rods is believed due to release of the pre-irradiation nitrogen impurity in the fuel at elevated temperatures. A release of 20 percent of this initial content would account for the 7 to 8 cm³ observed.

The distribution of the various xenon and krypton isotopes was found to agree well with that which would be predicted using the fission yields reported by Katcoff.^[12] The observed fractional release of xenon and krypton corresponds to 2.1 percent and 10.8 percent for the pellet and vipac rods, respectively. Calculations based upon the FIGHT code^[13] and a realistic axial and radial temperature distribution predict 1.5 percent and 9.0 percent for the xenon and krypton release for the pellet and vipac rods, respectively. The observed release for the vipac rods agrees reasonably well with that observed with vipac fuel irradiated at comparable temperatures in the Plutonium Recycle Test Reactor.^[14]

A gamma scan was taken of each of the four rods. A typical result is shown in Figure 4-1. Also shown are the locations of the various samples taken for the destructive analyses. Graphical integration of the gamma scan curves confirms the axial peak-to-average power ratio of 1.37.

TABLE 4-1

POST-IRRADIATION GAS SAMPLE ANALYSIS RESULTS

<u>Gas</u>	Gas Volume, cm ³ at STP			
	<u>X-1</u>	<u>X-5</u>	<u>D</u>	<u>E</u>
He	4.555	2.677	4.445	4.897
N ₂	7.970	9.881	0.047	0.018
O ₂	0.057	0.143	0.022	0.007
Ar	0.004	0.010	0.287	0.303
Kr	0.389	0.494	0.080	0.097
Xe	5.886	7.507	1.185	1.445
CH ₄	--	0.037	--	0.001
Total Volume	18.86	20.75	6.07	6.77

Figure 4-1 Gamma Scan of Saxton Rod D
(Showing Location of Samples)

Figure 4-2 EDGE TO CENTER COMPOSITE OF PEAK SECTION OF ROD A (150 x, ETCHED)

Metallographic examination of peak flux regions of both pellet and vipac rods revealed microstructures similar to those of unirradiated fuel. On the other hand, the usual radial cracks were evident in both full types; such cracks are typical of oxide fuel which has operated at low to moderate power levels. Also, the vipac fuel exhibited some evidence of in-reactor sintering near the radial center of the rod. In addition, the pellet fuel showed a slightly larger grain size at the center than at mid-radius or near the periphery. This evidence of equiaxed grain growth (and the absence of columnar grains) suggests a maximum center fuel temperature between 1400°C and 1700°C. This is consistent with a maximum observed power rating of 10.6 kw/ft, which corresponds to a peak center temperature of ~1500°C.

Two anomalies were observed in the materials evaluation of the vipac rod, X-1:

1. The cladding from the vipac rod showed an average hydrogen content approximately 18 ppm higher than that from the pellet rod; and
2. The inner surface of the cladding in the vipac rod had a 0.6 mil thick reaction layer.

In each case, calculations were made to identify the sources and estimate the consequences of the observed effect.

In the first case, above, chemical analyses of the fuel showed significantly higher moisture content in the vipac than in the pellet fuel, indicating that this extra moisture may be a possible source of the higher hydrogen content in the vipac cladding. Precise calculations are impossible, because several batches of fuel, of varying moisture and hydrogen content, were used for both the vipac and pelletized rods.

Examination of the chemical analyses of the various fuel batches shows 25 ppm as a reasonable value for the difference in moisture content for the two fuel types. If all of this moisture reacted and released hydrogen which was subsequently absorbed by the cladding, the clad hydrogen content increase would be 15 ppm. It is, therefore, reasonable to hypothesize that the higher moisture content of the vipac fuel is the source of the higher hydrogen content of the vipac cladding.

In investigating the second case noted above, the reaction layer was not identified positively. Calculations based on fuel chemistry show that the

extent of reaction cannot be explained on the basis of nitrogen or moisture impurities in the fuel. However, reduction of the hyperstoichiometric fuel (O/m 2.01-2.02) to stoichiometric during irradiation could release sufficient oxygen to account for the observed reaction layer.

Details of the metallographic examination of this low burnup fuel, including photomicrographs of representative fuel and cladding cross sections, are reported in Reference 9.

The burnup samples were analyzed for cesium-137, strontium-90, neodymium-148, and heavy-element isotopic ratios. The results of these chemical analyses were then used to infer a burnup for each sample. These inferred burnups are shown in Table 4-2 along with the burnup calculated based upon the reactor operating log and the average radial power factors for the particular fuel subassembly which contained these rods. Although the burnup inferred from the heavy element isotopic data was also calculated, some of the input data are suspect. Thus, the values are not reported. The discrepancy between the calculated and inferred values of burnup (average absolute percent difference ~10) is due in part to the use of average subassembly radial power factors. The power skewing effects known to exist across the subassembly were not considered in obtaining the calculated burnup. The algebraic average percent difference is only 2.4 percent. This is consistent with the reported [15] estimated error in measurement of burnup by the fission product method of ± 2 percent at 1 σ .

All evidence obtained through the post-irradiation examination of the low burnup fuel showed that both pellet and vipac plutonium-enriched mixed oxide fuel performed satisfactorily. Further, there was no indication of problems which would limit the performance of the rods at the power levels and burnups expected for the duration of Core II.

4.3 OVERPOWER TEST PROGRAM

4.3.1 Purpose of Overpower Test

The Overpower Test was designed to demonstrate that mixed-oxide fuel can withstand short duration overpower conditions after operation to moderately high burnup.

TABLE 4-2

FUEL BURNUP

<u>Sample</u>	<u>D-BU-1</u>	<u>D-BU-2</u>	<u>X-BU-1</u>	<u>X-BU-2</u>
<u>Inferred Burnup</u>				
Cs	6146	5520	5207	4881
Sr	6445	6143	5277	4819
Nd	6223	5514	5246	4717
Avg.	6305	5725	5243	4805
Calculated Burnup	6015	5210	6240	5240
<u>Calc-Inferred</u> <u>x100</u>				
Calc	-4.8	-9.9	16.0	8.3

4.3.2 Design of Overpower Test Subassembly

The overpower subassembly was similar to the regular removable Saxton 3 x 3 subassembly, except that 1) the lattice pitch was increased to provide power peaking in the test rods and 2) the enclosure can was non-perforated to permit independent flow sensing. Of the four fuel rod locations in the subassembly, two were occupied by removable fuel rods, while the remaining two contained a dummy rod and a flux wire thimble. Both fuel rods were the 9 x 9 removable type and had been irradiated in Core II from December, 1965, until February, 1967, when they were removed and examined visually during the extended shutdown. The subassembly was further instrumented by inlet and outlet thermocouples and a flow sensing pitot tube. This instrumentation provided data from which rod powers in the subassembly could be checked independently.

The overpower subassembly operated in the center of the Saxton core (N-1 location), and the test rods were the lead power rods in the core during the three months of the test. The core was flux-mapped to assure that neither the overpower test rods nor the standard mixed oxide peak rods exceeded their licensed power levels.

4.3.3 Test Operation

The overpower test was conducted in four steps. In the first, the test rods A and B operated at a nominal peak power of 15.5 to 16.0 kw/ft. Because the two rods had previously been irradiated at ~12 kw/ft, step one was used to pre-condition the fuel and to establish a base point for evaluations following overpower operation. Following the first step, the two rods were removed, visually examined, measured with a profilometer, and then returned to the center of the core.

Step two was the first phase of the actual overpower test, during which the rods reached a nominal peak power of 17.7 kw/ft. The test rods were first stabilized at 15.9 kw/ft for six days, and then the overpower step to 17.7 kw/ft was made as quickly as possible consistent with reactor operating limitations (approximately a two-minute escalation). The reactor was operated

to maintain the test rods at 17.7 kw/ft for five days, after which the reactor was shutdown.

The third step consisted of a second overpower irradiation. After ~4 days stabilization at 15.9 kw/ft, the test rods were operated continuously at 17.7 kw/ft for 15 days, except for a brief decrease to 15 kw/ft for 30 minutes and a return to 17.7 kw/ft.

The reactor was shutdown following the third step, and the decay constants of the flux wires were remeasured. The resulting data indicated that the previous power levels in the test rods were about 5 percent lower than anticipated. Therefore, the final overpower step (two days) was made at a higher reactor power level to compensate for this difference. The best estimate of the peak power achieved during this last step was 18.7 kw/ft. Table 4-3 summarizes the power levels during the various steps of the overpower test.

4.3.4 Examination of Overpower Test Rods

Visual

Visual examination of the test rods after pre-conditioning revealed no anomalous conditions. Comparison of profilometer traces made prior to and after pre-conditioning revealed only slight diameter changes. Pre-conditioning resulted in a generally lower diameter on rod A, typically 0.0003 to 0.0004 inch less, and little change in diameter in rod B. Changes deemed significant occurred at the bottom of both rods, where 0.0001 to 0.0005 inch decreases were observed. The profilometer precision was estimated to be ± 0.0002 inch.

After completion of the test and the shutdown of Core II, the overpower subassembly was shipped to the Post-Irradiation Facility for detailed examinations. Due to a cask insert fit-up problem, the overpower subassembly was damaged in shipment. A damage assessment revealed that although buckling of the subassembly can had occurred, no damage had been sustained by the test rods. The rods were removed from the subassembly, and visually examined. No anomalous conditions were observed.

The post-test profilometer traces suggest that the overpower test rods experienced slight diameter changes which tended to restore the rod diameter

TABLE 4-3

OVERPOWER TEST ROD OPERATING HISTORY

<u>Step No.</u>	<u>Period (1969)</u>	<u>Reactor (MWt) Power</u>	<u>Best Estimate Test Rod Peak Power (kw/ft)</u>
1	July 2-3	Escalating	0-15.9
1	July 4-11	22.3	15.8
2	August 9-11	21.8	15.4
2	August 13-19	22.6	15.9
2	August 19-23	25.6	17.7
3	September 3-6	22.6	15.9
3	September 6-21	25.6	17.7
4	October 17-18	26.7	18.7

to that which existed prior to pre-conditioning, i.e., the rod diameters determined after overpower generally fell between the previously measured values. In the top portion of each rod, however, the sequence of power changes resulted in a general diameter increase of approximately 0.0004 inches for both rods.

Rod CH was chosen as a reference rod from the group of high-burnup Saxton Core II rods which operated at highest linear power levels outside the overpower test assembly. This rod operated at a nominal peak linear level of ~ 12 kw/ft (with limited operation at ~ 13.5 kw/ft during power escalation) to a calculated rod average burnup of $\sim 21,000$ MWD/MTM. Rod D* was chosen as a reference rod representative of the operations of rods A and B, prior to any overpower operation. It had operated at a nominal peak linear power level of ~ 10 kw/ft to a calculated rod average burnup of 10,000 MWD/MTM.

Test fuel rods A and B and reference rods CH and D were subjected to extensive in-cell visual examinations, single channel γ -scanning, spiral trace profilometry, and length measurements.

The visual examination of test rods A and B revealed essentially the same conditions as seen during the previous underwater inspection. Both rods exhibited light crud deposits over the major portion of the surface area. There was no evidence of blisters, ridges, cracks, severe wear, white corrosion films, or other anomalies. High burnup reference rod CH was also free of anomalous surface conditions, except for numerous stain-like areas of irregular shape over much of the area between the bottom and top grids. These areas are believed to be associated with corrosion product deposits. On the other hand, the surface of reference rod D appeared predominantly black and lustrous, with very little evidence of crud deposits. This rod also showed no evidence of defects or other anomalous conditions.

* Note that this rod D is a removable 9 x 9 rod, and is a different rod than 3 x 3 removable rod D discussed in Section 4.2 of this report.

Gamma Scanning

All four of the rods were gamma scanned with a sodium iodide crystal detector and single channel analyzer, with total activity recorded at quarter inch intervals along each rod. The resulting scans were typical of irradiated Saxton fuel rods, showing flux depressions at grid locations and reflector peaking at the fuel column ends. The only anomalous condition was a possible gap between pellets of 0.25 to 0.50 in. on rod A, indicated by a 20 percent reduction in activity at ~31.5 in. from the bottom of the rod. The gamma scan data were later correlated with burnup measurements to help establish burnup distribution along the length of each rod.

Dimensional

The in-cell profilometry of rods A and B essentially confirmed the results obtained in the pool. Results on the two reference rods showed lower (by ~0.001 to 0.002 in.) mean diameters in the center regions than near the ends of the rods, with rod D exhibiting the greater difference. Typical ovalities were 0.002 in. but locally were as high as 0.003 to 0.005 inch. These trends are similar to those observed on other pellet-type rods examined in this program as discussed in Section 4.4.2.3 of this report. The profilometry data of rod CH more closely resembled that of the overpower test rods than did the results from rod D.

Rod lengths were measured with a dial gage indicator and a calibrated length standard. The results of the measurements are summarized in Table 4-4. They indicate rod length increases of 0.1 to 0.2 percent. These length changes are discussed further in Section 4.4.

Fission Gas Release

Each of the rods was punctured, and the fission product gases were collected and analyzed. As expected, the two overpower test rods showed higher fractional releases than the reference rods. Such differences are consistent with the higher fuel temperatures experienced by the overpower test rods. Similarly, the higher burnup reference rod (CH) had a greater release than rod D. These results are discussed further as part of Section 4.4, where data from all fission gas measurements are reported and evaluated.

TABLE 4-4

LENGTH CHANGES IN OVERPOWER TEST FUEL RODS

<u>Rod Identity</u>	<u>Calculated Peak Burnup (MWD/MTM)</u>	<u>Initial Length (In.)</u>	<u>Final Length (In.)</u>	<u>% Change</u>
A	20,800	41.633	41.679	0.11
B	19,700	41.608	41.673	0.16
D	13,300	41.636	41.684	0.12
CH	27,500	39.067	39.142	0.19

Metallography

Metallographic sections from the peak heat flux regions of rods A and B exhibited limited columnar grain growth and formation of an incipient central void, one of which is illustrated in Figure 4-2. Fission product precipitates also are visible in the high temperature central regions. In contrast to rods A and B, the peak heat flux region of rod CH exhibited only equiaxed grain growth. Small fission product precipitates were noted throughout most of the fuel at grain boundaries.

The α -autoradiographs in the peak sections of rods A and B, (Figure 4-3) indicate significant homogenization of the PuO_2 to about 50 percent of the pellet radius. The extent of homogenization agrees well with the limit of small columnar growth. The β - γ autoradiographs of rods A and B exhibit typical features for fuel which has experienced columnar grain growth, including bands of high fission product activity and adjacent areas of low activity. Radiographs of the peak section of rod CH are shown in Figure 4-4. In comparison with rods A and B, these radiographs indicate a lower fuel center temperature by the absence of bands of activity. This observation is consistent with the (13.5 kw/ft) peak power level for this fuel rod.

The observed fuel microstructures (absence of significant columnar grain growth or well-defined central void) in rods A and B were not consistent with operation at the originally anticipated overpower test conditions (up to 21.5 kw/ft). Because of these inconsistencies, the nuclear operating data, design data, temperature calculation methods, and metallographic results were completely reviewed. As a result, the best estimate of peak linear power in rods A and B was revised to 18.7 kw/ft. Other rod power levels during the various steps of the overpower test were shown in Table 4-3.

The nominal peak linear power of 18.7 kw/ft appears to be consistent with the observed fuel microstructures in the overpower test rods.

4.4 END-OF-CORE II-LIFE EXAMINATIONS

4.4.1 Underwater Examinations at WPIF

Following Core II shutdown on October 18, 1968, seven of the nine fuel assemblies

PHOTOMACROGRAPH

α -AUTORADIOGRAPH
(WHITE AREAS REPRESENT
HIGH α ACTIVITY)

β - γ AUTORADIOGRAPH
(DARK AREAS REPRESENT
HIGH β - γ ACTIVITY)

Figure 4-3. Peak Heat Flux Region - Rod A

PHOTOMACROGRAPH

α -AUTORADIOGRAPH
(WHITE AREAS REPRESENT
HIGH α ACTIVITY)

β - γ AUTORADIOGRAPH
(DARK AREAS REPRESENT
HIGH β - γ ACTIVITY)

Figure 4-4. Peak Heat Flux Region - Rod CH

containing $\text{PuO}_2\text{-UO}_2$ were shipped to the Westinghouse Post-Irradiation Facility. Each of the seven assemblies was visually examined for overall mechanical condition, crud deposits, and evidence of defects. The examination revealed buckling of the stainless steel enclosures on six of the seven assemblies. Seven fuel rods from the central plutonium assembly (Core Location D3) were removed and visually examined to determine whether the buckling of the enclosure had damaged any fuel rods. The examination showed no such evidence. Furthermore, evaluation of the effects of the buckling indicated that it would not impair interpretation of data in the program of post-irradiation examination.

Examination of both the fuel assemblies and individual rods revealed significant crud deposits on many fuel rods in the outer rows, particularly in corner positions. A large fraction of the crud appeared to be soft and non-adherent and was easily stirred loose during rod handling operations. Also, some of the crud had obviously been removed during withdrawal of the rods from the assemblies, as shown by the four crud-free scratch paths on each rod corresponding to grid contact positions.

4.4.2 Examination of Fuel Rods in Hot Laboratory

4.4.2.1 *Sampling Plan*

The selection of samples for the post-irradiation examinations of fuel rods irradiated throughout Core II was based on the following:

1. Materials evaluation emphasized fuel and cladding samples which had experienced the most severe operating conditions. Such samples provide the most significant data on clad oxidation and hydrogen absorption, changes in mechanical properties of the Zircaloy cladding, fuel rod dimensional changes, structural changes in the fuel, and fuel-clad interactions. Nine rods were selected from near the center of the core, all from areas of moderate to high thermal flux perturbation, i.e., high power positions. Three of these rods were from the center assembly (Core Location D3), two were from C3, one from E2, and the other three were removed from vipac assembly D4.

2. The majority of physics samples for burnup and isotopic analyses were taken from rods which had operated in an asymptotic neutron spectrum, i.e., least perturbed thermal flux. Five rods were selected, three from the center of Assembly C3 and the other two from the center of vipac Assembly D4. All five of these rods were representative of intermediate power rods and were also typical of "average" burnup fuel in the plutonium region. Physics samples were also taken from the high power rods to help establish peak burnups and distribution of burnup in the perturbed neutron spectrum region. The basis for the physics sampling plan is discussed further in another report.^[11]

The basic sampling plan is summarized in Table 4-5; locations of the assemblies and rods sampled are indicated in Figure 4-5.

4.4.2.2 *Visual Examination of Individual Fuel Rods*

Visual examinations conducted with the aid of an incell stereo viewer showed that most of the rod surfaces were covered with a thin, dark-gray, non-lustrous film of crud. These deposits appeared to be heavier and somewhat patchy in the high power locations, generally in the center 20 inches of each rod. An example of one of the patchy areas is shown in Figure 4-6. The thickness of the crud film near the center of rod TT, as determined by Filar eyepiece measurements, was in the range of 0.2 to 0.6 mil. Crud thickness in other areas of Rod TT and on other rods examined in the Hot Laboratory were estimated to be less than 0.5 mil in all cases.

All of the rods exhibited handling scratches and axial score marks, the latter resulting from removal of the rods past the grid contact points. In the areas of the scratches, it was evident that most of the crud film was soft and non-adherent. The axial score marks varied in width and were intermittently bright, indicating varying frictional forces during removal of the rods past the grid contacts.

All fuel rods were examined closely for crud patterns, excessive wear, and fretting, particularly at grid locations. Generally, the crud patterns were altered in the areas of grid contact, indicating a change in coolant flow

TABLE 4-5

SAMPLING PLAN FOR POST-IRRADIATION EXAMINATION

Rod No.	Assem. Loc.	Rod Loc.	Type/Purpose	Met.	Tensile	Burst	Mn-54	Clad H	HE	Nd-148	Am-241,243 Np-237	Pu-236, -238	Cs-137	α Auto.	β - γ Auto.
QE	C3	A1	P/M	5			4	4	1	1				1	1
TI	D3	A1	P/M	2	2	2		2	1	1				1	1
TP	D3	D1	P/M	2	1	1			1	1					
LA	E2	A1	P/M	2	1	1	2	2	1	1					
TE	C3	D1	P/M,P	2	1	1		2	3	3					
TT	E3	A6	P/M	2	2	2	2		1	1					
RI	C3	E4	P/P,R						18	18	3	3	10		
MY	C3	D5	P/P		1	1			3	3	3	3			
JF	C3	E5	P/P						3	3		3			
K4	E4	A1	V/M	5	1	1		4	1	1				1	1
N1	E4	A4	V/M	2	1	1			1	1					
N3	D4	A2	V/M	2	1	1			1	1					
S1	D4	D5	V/P						5	5		3			
PO	D4	E5	V/P						4	4		3			
A	2 x 2	2 x 2	P/OP	2				2	1	1				1	1
B	2 x 2	2 x 2	P/OP	2				2	1	1				1	1
D	Out	Out	P/OP/ref	2				2	1	1					
CH	D3	D9	P/OP/ref	2				2	1	1					

Notes: 1. Type: P - pellet fuel, Zircaloy clad
V - Vipac fuel, Zircaloy clad

2. Purpose: M - materials performance evaluation
P - physics performance evaluation
R - radial sample
OP - overpower test rod
ref - overpower reference rod (D has similar burnup w/o high kw/ft; CH has similar kw/ft with high burnup)

3. All rods receive: visual exam., with photos as needed; profilometer and length measurements; fission gas sampling and analysis; single-channel γ -scan.

4. Rod RI receives multi-channel γ -scan with and without cladding.

5. Radial sample includes 10 samples drilled from different radii with analyses for Cs-137, HE, and Nd-148. In addition, α and β - γ autoradiographs and metallurgical mounts will be prepared.

6. "HE" includes U-234, -235, -236 and -238; Pu-239, -240 -241, and -242; and Pu-239/U-238. In addition to samples indicated, five archive samples will be analyzed.

ASSEMBLY LOCATIONS IN CORE

A1	A2	A3	A4	A5	A6	A7	A8	A9
B1								B9
C1								C9
D1							D8	D9
E1							E8	
F1							F8	
G1							G8	
H1			H4	H5	H6	H7	H8	
J1	J2	J3	J4	ROD LOCATIONS IN ASSEMBLIES				

Figure 4-5. Nomenclature for Rod and Assembly Locations in Saxton Plutonium Program

PHOTO 4150

4X

Figure 4-6. Example of Patchy-type Crud near the Center of Rod TI

around the grids. Figure 4-7 shows typical crud patterns near grids; note the apparent reduction in crud immediately adjacent to the grid contact points. Although the grid-to-clad contact areas were obvious on all rods, there was no evidence of significant fretting except at a bottom grid location on one Vipac fuel rod. In this instance, the deepest of the fretted areas, shown in Figure 4-8, was measured as 0.110" long x 0.085" wide x 0.015" deep. A one-inch long section containing the major fretted areas was removed from the rod for subsequent metallographic study, the results of which are discussed in section 4.4.7 of this report. More typical grid-clad contact areas, which exhibited no significant wear or fretting, are shown in Figure 4-9.

None of the visual examinations of the 14 rods in the basic sampling plan showed evidence of clad cracks, swelling, hydride blisters, ridging, white oxide film or other anomalies.

4.4.2.3 Dimensional Measurements

Length measurements were performed by placing each fuel rod in a special fixture and observing the deflection on a dial indicator compared with that for a rod of calibrated length. As shown in Table 4-6, all rods increased in length by 0.14 to 0.22 percent, with pellet rods showing slightly higher increases. The data also suggest a trend toward greater increases with higher burnup.

Each fuel rod was scanned with an in-cell profilometer, which provided a spiral trace of diameter as a function of axial position. A portion of a typical profilometer trace is shown in Figure 4-10. The results were as follows:

1. When compared with diameters near the top and bottom of each rod, diameters were less over the center 30 in. The differences between minimum and end-of-rod diameters ranged between 0.001 and 0.0025 in., which represents about a 0.2 percent to 0.6 percent diameter decrease. These reductions in fuel rod diameter are qualitatively consistent with original design predictions.^[3]
2. Ovalities were typically about 0.001 in., but locally as high as 0.0035 inch. Vibratory-compacted fuel rods generally showed less ovality.

↑
COOLANT FLOW
DIRECTION

PHOTO 4182
TOP GRID LOCATION, ROD PO

4X

↑
COOLANT FLOW
DIRECTION

PHOTO 4173
SECOND-FROM-BOTTOM GRID, ROD SI

4X

Figure 4-7. Typical Crud Patterns at Grid Contacts

PHOTO 4194

4X

Figure 4-8. Significant Fretting at Bottom Grid Location of Vipac Rod K4

PHOTO 4206
TOP GRID LOCATION, ROD TE

4X

PHOTO 4180
SECOND-FROM-BOTTOM GRID, ROD PO

4X

Figure 4-9. Typical Grid-toCladding Contact Areas

TABLE 4-6

SAXTON CORE II FUEL ROD LENGTH CHANGES

<u>Rod Number</u>	<u>Fuel Type</u>	<u>Rod Location</u>	<u>Measured Rod Average Burnup, MWD/MTM</u>	<u>Final Length, In.</u>	<u>Original Length, In.</u>	<u>Length Increase, In.</u>	<u>Length Increase, %</u>
TI	Pellet	D3-A1	17,400	39.139	39.074	0.065	0.17
EC	Pellet	D3-A4	19,100	39.152	39.080	0.072	0.18
TP	Pellet	D3-D1	19,700	39.155	30.075	0.080	0.20
TT	Pellet	D3-A6	20,000	39.133	39.066	0.065	0.17
QE	Pellet	C3-A1	20,700	39.150	30.067	0.083	0.21
TE	Pellet	C3-D1	20,700	39.143	39.069	0.074	0.19
LA	Pellet	E2-A1	17,800	39.134	39.065	0.069	0.18
MY	Pellet	C3-D5	14,900	39.144	39.058	0.086	0.22
RI	Pellet	C3-E4	14,900	39.128	39.065	0.063	0.16
JF	Pellet	C3-E5	14,800	39.145	39.069	0.074	0.19
K4	Vipac	D4-A1	20,400	39.087	39.020	0.067	0.17
N3	Vipac	D4-A2	19,300	39.089	39.028	0.061	0.16
N1	Vipac	D4-A4	20,700	39.089	39.024	0.065	0.17
S1	Vipac	D4-D5	15,700	39.075	39.020	0.055	0.14
PO	Vipac	D4-E5	15,300	39.083	39.024	0.059	0.15

Figure 4-10. Typical Portion of Spiral Profilometer Trace, Rod TP

3. Mean diameters ranged from 0.3939 to 0.3888 in, as compared with pre-irradiation diameters of 0.392 ± 0.002 in.
4. There was no evidence of gross fuel rod swelling, local hydride blisters, or longitudinal ridging.
5. Several pellet rods showed evidence of slight clad ridging at pellet interfaces. The extent of this ridging was typically 0.0005 in. and never greater than 0.001 inch.

Figures 4-11, 4-12, and 4-13 summarize the variation in mean diameters as a function of axial position for three groups of rods: 1) high burnup pellet rods, 2) intermediate burnup pellet rods, and 3) high burnup vipac rods. Note that the mean diameters of the three high burnup vipac rods were greater than those of the pellet rods along their entire length. Moreover, the diameters near the center of the vipac rods were approximately the same as end-of-rod diameters, reflecting the support provided by the vipac fuel throughout operation. The two intermediate burnup vipac rods exhibited widely differing diameters. The reason for the large difference is not known. However, it may be attributed, in part, to differences in pre-irradiation (after pickling) tubing diameters. The results of the in-cell profilometry for all rods scanned in this program are presented in Reference 16.

4.4.2.4 *Gamma Scans*

Nineteen fuel rods were scanned with a sodium-iodide scintillation crystal detector. The gamma activity data, consisting of 10-second counts at quarter-inch intervals, are summarized in Table 4-7. These data indicate relative rod average burnups and help establish locations for burnup and metallographic samples. The overall results of the gamma scans and the relationship between gamma activity and burnup are discussed further in Reference 11.

4.4.2.5 *Fission Gas Release Measurements*

All 18 fuel rods listed in the sampling plan were punctured in a calibrated vacuum system to collect and sample internal gases. In addition, each rod was helium leak-tested after puncturing; no leaks were detected. Samples of the released gases were analyzed by mass spectrometry. The results of fission gas analyses are given in Table 4-8. Measured fractional release values are

Figure 4-11. Summary of Profilometer Data for High Burnup Pellet Rods

Figure 4-12. Summary of Profilometer Data for Intermediate Burn-up Feltet Rods

Figure 4-13. Summary of Profilometer Data for High Burnup Vipac Rods

TABLE 4-7

SUMMARY OF SINGLE-CHANNEL GAMMA SCAN DATA

<u>Rod No.</u>	<u>Fuel Type</u>	<u>Irrad. Time (Days)</u>	<u>Cooling Time (Days)</u>	<u>Peak-to-Ave. Ratio</u>
JF	Pellet	406	102	1.34
RI	Pellet	406	102	1.35
MY	Pellet	406	103	1.37
QE	Pellet	406	112	1.32
TE	Pellet	406	115	1.33
TT	Pellet	406	82	1.47
EC	Pellet	406	82	1.38
TT	Pellet	406	82	1.37
TP	Pellet	406	102	1.40
CH	Pellet	406	115	1.33
LA	Pellet	406	115	1.48
S1	Vipac	406	102	1.33
P0	Vipac	406	102	1.32
K4	Vipac	406	102	1.31
N1	Vipac	406	103	1.32
N3	Vipac	406	103	1.32
A	Pellet	322	60	1.32
R	Pellet	322	60	1.32
D	Pellet	278	492	1.53

TABLE 4-8

FISSION GAS RELEASE DATA, SAXTON PLUTONIUM FUEL RODS

Rod No.	Rod Location ^a	Measured Rod Average Burnup MWD/MTM	Volume of Gas Released ^b , cm ³	Gas Composition, Mole Percent				Xe	Measured Fractional Release, %	Calculated HFP-EOL Rod Pressure psia
				He	N ₂	Ar	Kr			
TI	E3-A1	17,400	79.4	8.4	0.1	0.1	5.6	85.8	31	1230
TP	De-D1	19,700	86.6	8.3	0.1	0.4	5.4	85.8	30	1510
TT	E3-A6	20,000	91.5	6.1	0.1	0.4	5.5	87.7	32	1150
QE	C3-A1	20,700	74.4	9.6	0.1	0.5	5.3	84.5	24	1630
TE	C3-D1	20,700	87.4	8.6	0.1	0.4	5.3	85.6	29	1490
LA	E2-A1	17,800	55.1	10.0	0.2	0.6	5.3	83.8	21	300
MY	C3-D5	14,930	28.6	15.2	0.1	1.0	5.1	78.6	12	350
RI	C3-E4	14,900	14.3	22.6	0.5	3.9	4.6	68.2	5	210
JF	C3-E5	14,800	13.0	39.7	0.2	3.4	3.6	53.1	4	200
K4	E4-A1	20,400	114.2	8.7	5.6	0.1	4.5	81.0	37	1450
N1	E4-A4	20,700	115.6	8.6	7.0	<0.1	4.4	79.7	36	1700
N3	E4-A2	19,300	[Sample lost during puncturing]							1380
S1	E4-D5	15,700	30.1	22.4	0.1	<0.1	4.5	73.0	12	210
PO	E4-E5	15,300	27.1	28.0	0.2	<0.1	4.5	67.3	10	290
A	C/P 2 x 2	15,400	82.5	8.3	1.4	0.5	5.1	84.7	35	1230
B	C/P 2 x 2	15,400	81.9	7.4	1.4	0.5	5.2	85.4	36	980
D	E3-E1	9,300	34.0	26.0	14.0	4.8	3.1	50.8	15	190
CH	E3-D9	20,500	82.4	9.1	0.3	0.6	5.1	84.9	25	1020

^aSee Figure 4-5 for Rod Location nomenclature^bCorrected to STP

included based on measured rod average burnup. As expected, the rods with higher heat ratings showed greater gas release. The volume of gas collected from each of the two high-burnup vipac rods was greater than for any pellet rod. Part of the difference in gas release between pellet and vipac rods is due to the nitrogen released from the higher temperature regions of the vipac fuel, the source of the nitrogen being the atmosphere in which the arc-fused UO_2 was prepared. All rods showed significant helium in the collected gases. The principal source of the helium is the original backfill atmosphere although some is produced by ternary fission. The presence of argon in the pellet rods is attributed to the in-box welding atmosphere which consisted of 10 percent argon and 90 percent helium.

The design basis used in setting the fuel rod plenum size was to assure that the hot full power end-of-life rod internal pressure would be less than the primary system coolant pressure at a maximum rod average burnup of 20,000 MWD/MTM.^[3] This criterion was well satisfied by the highest burnup rods (20,700 MWD/MTM rod average burnup) as shown in the last column of Table 4-8.

4.4.2.6 *Metallographic Examinations*

General

A total of 49 samples were removed from fuel rods and mounted for metallographic examination. The location of the samples, relative power levels, and major purpose for each examination are given in Table 4-9.

Macroexamination

Examination of the mounted samples at low magnification revealed the usual crack patterns in the fuel, typical of oxide fuel which had operated at linear heat ratings of ~ 7 -15 kw/ft. The cracks were predominantly radial in the lowest power sections; however, both radial and circumferential cracks were clearly evident in the peak and near peak power sections, as for example in rod QE, shown in Figure 4-14. This observation is consistent with those made in previous CVTR and Yankee fuel examinations. The macrographs also showed no evidence of a central void or columnar grain growth. In light of the power history of these rods (~ 13.5 kw/ft maximum linear power) neither would be

TABLE 4-9

SUMMARY OF METALLOGRAPHIC EXAMINATIONS

<u>Rod Serial Number</u>	<u>Axial Location of Sample, In. From Bottom</u>	<u>Sample Orientation</u>	<u>Power Relative to Rod Peak</u>	<u>Major Emphasis of Examination</u>
QE	17.8	T	1.00	Clad oxidation and hydriding, Fuel structure as function of local power
QE	25.0	T	0.93	" " "
QE	30.0	T	0.75	" " "
QE	35.0	T	0.45	" " "
QE	38.0-39.0	L	----	Top of clad & end closure weld
TI	17.8	T	1.00	Clad oxidation and hydriding, Fuel structure at peak power position
TE	33.5-34.5	L	0.60	Clad structure in grid contact area
TP	14.0-15.0	L	0.93	" " "
TT	14.3-15.3	L	0.90	Cladding structure in grid contact area
K4	4.3	T	0.60	Clad fretting at bottom grid contact
K4	17.7	T	1.00	Vipac fuel structure at peak power position
LA	17.7	T	1.00	Clad, fuel structure at peak power position
TP	19.7	T	1.00	" " "
TT	19.7	T	1.00	" " "
N1	19.7	T	1.00	" " "
N3	19.7	T	1.00	" " "
N1	14.0-15.0	L	0.92	Clad structure in grid contact area
N3	14.0-15.0	L	0.92	" " "
LA	0.0-1.0	L	<0.50	Bottom of fuel and end closure

TABLE 4-9 (Continued)

SUMMARY OF METALLOGRAPHIC EXAMINATION

<u>Rod Serial Number</u>	<u>Axial Location of Sample, In. From Bottom</u>	<u>Sample Orientation</u>	<u>Power Relative to Rod Peak</u>	<u>Major Emphasis of Examination</u>
TI	0.0-1.0	L	<0.50	Bottom of fuel and end closure
K4	25.0	T	0.92	Clad, Vipac fuel structure at partial power
K4	30.0	T	0.75	" " "
CH	8.0	T	0.90	Clad oxidation, corrosion product films
CH	28.5	T	0.75	" " "
CH	23.8	T	0.85	Clad oxidation, corrosion product films
CH	26.4	T	0.80	" " "
CH	27.3	T	0.75	" " "
CH	28.3	T	0.75	" " "
QC	21.7	T	0.95	" " "
TE	17.7	T	1.00	" " "
ML	10.8	T	0.95	Local Clad Hydriding
ML	11.0-12.0	L	0.95	" " "
ML	13.0	T	0.95	" " "
ML	19.0	T	1.00	" " "
ML	4.5	T	0.60	" " "
ML	25.0	T	0.85	" " "
ML	32.5	T	0.60	" " "
MG	13.6	T	0.90	" " "

TABLE 4-9 (Continued)

SUMMARY OF METALLOGRAPHIC EXAMINATIONS

<u>Rod Serial Number</u>	<u>Axial Location of Sample, In. From Bottom</u>	<u>Sample Orientation</u>	<u>Power Relative To Rod Peak</u>	<u>Major Emphasis of Examination</u>		
MO	8.0	T	0.85	Local Clad Hydriding		
MO	10.8	T	0.90	Local Clad Hydriding		
MO	17.8	T	1.00	"	"	"
MO	22.7	T	0.95	"	"	"
MY	9.7	T	0.90	"	"	"
MY	18.7	T	1.00	"	"	"
MY	19.7	T	1.00	"	"	"
LI	22.7	T	0.95	"	"	"
RA	9.5	T	0.90	"	"	"
RA	20.6	T	0.95	"	"	"
TM	9.1	T	0.90	"	"	"

4232 ~8X
35 IN. FROM BOTTOM, 0.45 OF PEAK POWER

4233 ~8X
30 IN. FROM BOTTOM, 0.75 OF PEAK POWER

4334 ~8X
25 IN. FROM BOTTOM, 0.93 OF PEAK POWER

4335 ~8X
17.8 IN. FROM BOTTOM, ~PEAK POWER POSITION

Figure 4-14, Photomicrographs of Four Transverse Sections from Rod QE

expected. Another feature of the macrographs was the larger apparent fuel-to-clad gap in the low power sections as compared with those of high power. This observation is consistent with the profilometer measurements, which showed at least partial closing of the gap at the higher power positions.

Autoradiography

Autoradiographs, both alpha and beta-gamma, of representative peak power sections showed homogenization of the center area of the fuel out to $\sim 1/3$ radius (Figure 4-15). Such homogenization is consistent with expectations for mixed oxide fuel of moderate power rating and has been observed previously. The higher alpha activity near the periphery of the fuel, due to the greater plutonium higher isotope production in this region, is shown clearly in the α -autoradiograph.

Clad Microstructure

The microstructure of the Zircaloy cladding was examined for the following features:

1. Oxidation of outer and inner surfaces
2. Concentration and orientation of zirconium hydrides
3. Fuel-clad interaction
4. Anomalous conditions such as cracks, local hydriding, or evidence of locally high temperatures

OXIDATION OF OUTER SURFACE - The samples exhibited outer oxide layers of varying thickness. The initial examinations of cladding from peak power locations revealed locally thick, somewhat porous oxide on certain rods (e.g. CH, TE, and TT). On the other hand, several samples from high power positions showed relatively thin, adherent oxide films. In other sections, it was difficult to measure precisely the oxide thickness due to apparent film loss during handling or metallographic preparation. Examples of these conditions are shown in Figures 4-16, 4-17, and 4-18.

The results of the initial examinations are summarized in Table 4-10. Included in this Table are predicted values of oxide thickness for each metallographic section. These predictions were based on analyses of the thermal history of

ALPHA ~8X
(WHITE SPOTS REPRESENT HIGH α ACTIVITY.)

BETA-GAMMA ~X8
(DARK SPOTS REPRESENT HIGH β - γ ACTIVITY.)

Figure 4-15. Autoradiographs of Peak Power Section of Rod QE

Figure 4-16. Typical Appearance of Oxide Film on Outer Surface of Rod QE at Peak Power Position

681.5

500X

Figure 4-17. Relatively Thick, Patchy Oxide-Type Layers on
Outer Surface of Rod TT

741.6

500X

742.12

500X

Figure 4-18. Patchy Oxide-Type Layers on Outer Surface of Rod CH

TABLE 4-10.

SUMMARY OF OXIDE FILM MEASUREMENTS - SAXTON CORE II FUEL RODS

Rod Number	Section ^a (Inches)	Heat Flux ^b (BTU/hr-ft ²)	Irradiation Time (EFPH)	Predicted Oxide Thickness (mils)	Actual Oxide Thickness (mils)
A	18	621,300	7,410	0.11	0.10-0.15
	25	499,900		0.09	≈0.10
B	18	621,200	7,410	0.11	0.20-0.25
	25	500,000		0.09	0.10-0.15
D	18	260,500	6,350	0.08	0.10-0.12
	25	205,700		0.07	0.08-0.10
CH	9	375,000	9,380	0.15	0.10-0.50
	18	398,000	9,380	0.15	0.40-0.75
	29	305,000	9,380	0.11	0.20-0.70
QE	18	400,000	9,380	0.15	0.15-0.40
	25	353,000	9,380	0.14	0.09-0.25 ^c
	30	306,900	9,380	0.11	0.10-0.35
	35	175,000	9,380	0.06	0.05-0.06
K4	5	----	9,380	<0.1	<<0.10
	18	----	9,380	---	0.08-0.15
	30	----	9,380	---	0.25-0.30
TI	18	400,000	9,380	0.15	0.08-0.50
TE	18	400,000	9,380	0.05	0.20-0.70
	34	201,600	9,380	0.06	0.05-0.08
TT	15	382,000	9,380	0.15	0.10-0.15
	20	400,000	9,380	0.15	0.10-0.60
N3	15	----	9,380	---	0.08-0.10
	19	----	9,380	---	0.05-0.07
N1	15	----	9,380	---	0.06-0.10
	18	----	9,380	---	0.10-0.50
LA	18	400,100	9,380	0.15	0.08-0.10

^aDistance from bottom end of rod^bValues immediately prior to test termination^cPossible loss of oxide at several locations

the rods using out-of-reactor corrosion kinetics of Zircaloy-4. A comparison of the predicted values and measured oxide film thicknesses shows that:

- a) Overpower rod A and reference overpower rod D have thin, uniform, adherent oxide films in accordance with prediction. Overpower rod B has a thicker than predicted oxide film at the peak flux location (18 inches from bottom of the rod) but not at the 25 inch location.
- b) Samples at or adjacent to the peak heat flux location (18 inches) exhibited abnormally thick oxide films on certain rods with high variability in thickness around the rod circumference. Three rods (LA, N3, K4) had uniform, thin oxide films of 0.1 to 0.2 mil, which is in good agreement with the predicted value of 0.15 mil. Rod CH exhibited heavy oxidation at all circumferential locations, the oxide film being non-adherent, porous, and at least 0.4 mil thick. All other rods showed a wide variation in oxide film thickness, with some areas of thin adherent oxide film (0.1 to 0.2 mil) in accordance with predictions, and other areas exhibiting thick oxide films of 0.4 to 0.7 mil, such as shown in Figure 4-17. In a few cases, the oxide film was heavily cracked and there was evidence of oxide loss in handling.
- c) Longitudinal sections on four rods taken at the 15 inch position (which was a grid location) showed uniform, thin, adherent oxide films of 0.10 to 0.15 mil, that is, in accordance with prediction.
- d) Rod QE was examined at locations 25 inches, 30 inches, and 35 inches from the rod bottom in addition to the 18 inch position (peak heat flux location). There was no evidence of excess oxidation at 25 inches. At 30 inches there was occasional patchy oxidation similar to that observed at 18 inches, with some heavy oxidation (up to 0.35 mil) and some thin, uniform films of 0.10 to 0.15 mil. At 35 inches there was no enhanced oxidation.
- e) Rod CH exhibited very uneven oxidation at nine inches from the rod bottom (generally 0.3 to 0.5 mil) with one area of thin (0.1 mil), uniform oxidation. At the 29 inch location, oxidation was generally

variable but always greater than predicted, varying from 0.2 to 0.7 mil in thickness. Figure 4-18 illustrates the variable nature of the oxide at two different axial locations on rod CH.

- f) Sections on rod K4 at 5 inches and rod TE at 34 inches both showed thin, adherent oxide films (0.05 to 0.08 mil), in agreement with predictions.

Because of their porous and non-adherent nature, certain of the layers were, at first, tentatively identified as crud. However, closer examination of several additional sections and chemical decrudding of the outer surface of suspect rods, indicated that the thick films were probably zirconium oxide of highly variable density and thickness. As part of this study, five sections from rod CH were studied, primarily because this rod had exhibited numerous patchy, stain-like areas and apparent residual crud during its visual examination. Sections from near the peak power sections of rods QE and TE also were examined. Prior to mounting, each of the sections was photographed to document surface features as related to circumferential orientation marks. Examples of the patchy conditions seen on rod CH are shown in Figure 4-19.

The comparison of surface features and structure of oxide layers indicated that there was no direct correlation between the two. When black, non-lustrous patches were observed, however, they usually were associated with thick oxide layers (>0.4 mil). On the other hand, some samples showed thick oxide in areas of normal surface appearance, i.e., free of dark, stain-like patches. Furthermore, there were many locations where surface features varied considerably, but where the oxide thickness remained uniform. In addition, residual crud up to 0.4 mil frequently was observed in areas of thick oxide (and dark, patchy surface appearance) and also, occasionally, where oxide layers were thin. The presence of residual crud, however, could not be correlated consistently with the appearance of fuel rod surface. Figures 4-20 and 4-21 show several of the conditions discussed above.

The additional metallographic studies of samples from rods CH, QE, and TE confirmed the significant local variability in oxide thicknesses, noted above. The thickest oxide layers observed were in the range of 0.5 to 0.8 mil, which were essentially the same as those of other sections of the same rods. It

MACRO 4801

~4X

~8.5 IN. FROM BOTTOM OF ROD

MACRO 4807

~4X

~29 IN. FROM BOTTOM OF ROD

Figure 4-19. Dark, Non-Lustrous Patchy Areas on Outer Surface of Rod CH

812.2

500X

Figure 4-20. Intermittent Oxide Film in Area of Uniformly Dark, Non-Lustrous Surface, 27.3 Inches from Bottom of Rod CH

Figure 4-21. Thick Oxide Layer Associated with Dark Non-Lustrous Surface, 28.5 Inches from Bottom of Rod CH

should be noted that there was no evidence of an associated increase in hydrogen absorption in samples which exhibited the thick oxide.

OXIDATION OF INNER SURFACE OF CLADDING

All of the pellet fuel-bearing sections exhibited an oxide-type layer, typically 0.2 to 0.3 mils thick, on the inner surface of the cladding. Metallographically, the layer resembled the ZrO_2 film on the outer surface. Since there is sufficient oxygen released from the fuel during fissioning, especially at higher burnup, it is reasonable to assume that this reaction layer is indeed zirconium oxide. The layer was more evident in the higher burnup samples; it tended to be thicker and was observed over a greater fraction of the inner surface. The low and intermediate burnup samples generally had intermittent oxide films, less than 0.3 mil in thickness. Typical photomicrographs illustrating these inner surface layers are shown in Figures 4-22 and 4-23.

The inner surface of the vipac fuel rods also exhibited an oxide-type layer. In most samples, the layer varied in thickness from 0.1 to 0.5 mil and appeared to be bonded to fuel particles, as shown in Figures 4-24 and 4-25. The source of the oxygen in these rods is believed to be the same as in the pellet-type rods, i.e. excess oxygen from the UO_2 - PuO_2 fuel after significant fissioning. In addition, the vipac fuel was known to be slightly hyperstoichiometric, with oxygen-to-metal ratios of 2.01-2.02, while 13 of 15 batches of pellet fuel were slightly hypostoichiometric.

The examination of clad inner surfaces also revealed numerous areas where small pieces of fuel appeared to be bonded to the inner surface of the clad, suggesting that the fuel was in contact during at least some portion of operation. In most of these instances, the fuel particles were attached to the inner oxide layer, with an intermediate gray phase of unknown composition observed intermittently between the fuel and oxide layer. The typical appearance of this multiple interaction zone is shown in Figure 4-26.

HYDRIDE PRECIPITATION

With the exception of two cases of local hydriding to be discussed later in the report, hydrides in the clad microstructure appeared to be uniformly distributed, with random to circumferential orientation. Occasionally, the

Figure 4-22. Typical Appearance of Reaction Layer on Inner Surface of Cladding

MICRO 675.1 500X
15 IN. FROM BOTTOM OF ROP TP

MICRO 672.8 500X
25 IN. FROM BOTTOM OF ROD QE

Figure 4-23. Examples of Intermittent Oxide Layer on Inner Surface of Cladding

688.21
500X

180°
I.D.

690.13
STEP 3

500X

INNER
270°

Figure 4-24. Examples of Inner Surface Oxide on Vipac Fuel Rods

688.22

500X

Figure 4-25. Oxide-Type Layer on Inner Surface of Vipac Rod K4 at Peak Power Section

Figure 4-26. Examples of Fuel-Clad Interaction Showing Intermediate Gray Phase Between Fuel and Inner Surface Oxide Layer

hydrides clustered in a star-pattern near the center of the clad cross-section, but there was no evidence of massive hydriding or local radial hydriding. Furthermore, none of the samples showed any indication of stress re-orientation of hydrides. The hydrogen content, as estimated from micrographs of samples from QE, was in the range of 70 to 100 ppm. These estimates were confirmed by subsequent hydrogen analyses of ring samples cut from locations immediately adjacent to the metallographic specimens. The results were as follows:

<u>Sample Number</u>	<u>Distance From Bottom End of Rod, Inches</u>	<u>Hydrogen*, ppm</u>
QE-1	17.6	93
QE-2	25.1	88
QE-3	30.1	71
QE-4	35.1	78

* Based on average of two determinations per ring sample.

The above hydrogen analyses also agree well with the original predicted end-of-life hydrogen content of 71 ppm, based on peak burnups of 25,000 MWD/MTM.^[4] Extrapolation of the 71 ppm value for the higher peak burnups actually experienced in Saxton Core II would increase this to 80 to 85 ppm, which is close to the observed values.

Photomicrographs illustrating the nature of hydrides in typical clad samples (rod QE) are shown in Figure 4-27.

Since hydriding behavior was of particular interest near grids, four samples representative of grid contact areas were examined. All four samples exhibited a normal concentration and orientation of hydrides. There was no evidence of any significant wear of the cladding by the spring fingers and dimples.

However, as noted in Section 4.4.2.2, significant fretting was observed on vipac rod K4, between 4.0 and 5.0 inches from the bottom of the rod. There was evidence of cladding indentation at all six grid contact positions. One of the severely fretted areas (the spring contact location at about 4.25 inches from the bottom) was examined metallographically to determine its profile and to assess the extent of hydride precipitation.

MICRO 670.12

500X

35 IN. FROM BOTTOM, 0.45 PEAK POWER

MICRO 673.12

500X

17.8 IN. FROM BOTTOM, PEAK POWER POSITION

Figure 4-27. Cross-Section of Fuel Cladding from Rod QE Showing Typical Concentration and Orientation of Hydrides

The sample was examined at several planes after incremental grinding. The maximum depth and width of the major fret mark were 0.0085 inches and 0.121 inch, respectively. Figure 4-28 is a photomacrograph showing the extent of the fretting, of both the major fretted area and a smaller fret mark at 90 degrees to the larger one. The cladding microstructure at each plane was examined for outer surface oxide films and hydride orientation. Oxide layers on the non-fretted surfaces were generally thin (<0.1 mil). Mainly, this is due to the relatively low cladding operating temperatures at this location. On the other hand, there was no oxide film visible on any of the fretted surfaces, which suggests that the fretting action continuously removed any oxide formed during Core II operation. The examination also showed that the hydride orientations and concentrations were essentially the same as for the rods with similar burnup and power history. A composite photomicrograph (Figure 4-29) of the cladding at the center of the major fret mark illustrates the normal hydride conditions.

Longitudinal sections of end closure areas of several rods were examined especially for hydriding in the weld and heat affected zones. All evidence indicated that hydride concentrations in these areas were lower than elsewhere in the cladding. Furthermore, the hydride platelets appeared to be smaller and more uniformly distributed than in the fuel-bearing portions of the rods (Figure 4-30). These longitudinal samples were also examined for overall weld integrity, corrosion film thickness, and any unusual interaction among fuel, aluminum oxide spacer disc, cladding, and the end plug. In both samples, the welds appeared sound, and corrosion films were significantly thinner than on fuel-bearing sections of the same rods (less than 0.1 mil as compared with typical 0.1 to 0.2 mil films). There was no evidence in these microstructures of any interaction between the fuel and any of the other materials.

INVESTIGATION OF LOCAL HYDRIDING

Rod ML was held for further study because of anomalous dimensions observed during the Saxton Core III reconstitution program.^[16,17] Profilometer measurements had shown localized diameter variations which were 0.003 to 0.004 in. greater than nominal in an area 10 to 12 inches from the bottom of the rod. Subsequent puncturing of the rod for fission gas collection and

analysis indicated that the rod had not failed, i.e., there was no evidence of leaks, and the quantity and composition of the collected gas were normal for a rod of this burnup. Metallographic examination in this region revealed local hydriding near the outer surface and an associated thick oxide layer (~1.0 mil). Metallographic examination of adjacent sections also showed extensive hydriding near the outer surfaces (solid hydride in several locations) and relatively thick oxide where the hydriding was heavy. In several cross sections, cracking of the clad was observed, with the cracks originating at the inner surface and extending to a maximum of about 70 percent of the wall thickness. Figures 4-31 and 4-32 show typical areas of this portion of the rod. Examinations of a longitudinal section after several incremental grinding steps showed small amounts of solid hydride at the inner surface of the clad, suggestive of internal contamination. As shown in Figure 4-33, a transverse section at the peak heat flux region, about 19 inches from the bottom of the rod, also revealed surface hydriding and cracks in the cladding from the inner surface to about 25 percent of the wall thickness.

The investigation of hydriding in rod ML indicates an internal source of hydrogen, i.e., the inner portion of the clad was hydrided first, became embrittled, and then cracked. In time, most of the excess hydrogen diffused down the thermal gradient toward the cooler outer surface where it precipitated.

Three fuel rods which were adjacent to rod ML in Core II were examined closely for unusual surface features, especially at the axial position (10-12 in.), where ML exhibited hydriding. None of these rods exhibited any abnormal surface conditions.

Metallographic sections were removed from areas of four other rods which had shown anomalous dimensions (LI, MG, RA, and TM), during Core III reconstitution dimensional inspection. Of these, only one section -- 13.6 inches from the bottom of rod MG -- showed evidence of significant hydriding. On this sample, there was one small area of solid hydride near the outer surface but no cracks in the cladding and no evidence of thick oxide film in the hydrided zone.

A review of fabrication records showed that the two hydrided rods (ML and MG) contained fuel from pellet batch No.3. Therefore, two additional rods (MO and MY) containing fuel from this batch were examined metallographically.

4836

Figure 4-28. Photomicrograph of Transverse Section of Rod K4 Showing Depth of Fretting

90.28 - 31

100X

Figure 4-29. Typical Hydride Orientation at Fretted Area of Rod K4

4907 MACRO OF BOTTOM SECTION, TI

4.4X

685.10

HYDRIDES AT WELD OF ROD TI

100X

Figure 4-30. Appearance of Hydrides Near Bottom End Closure Weld, Rod TI

786.5

100X

Figure 4-31. Transverse Section Showing Local Hydriding of Rod ML,
10.8 Inches from Bottom of Rod

Figure 4-32. Longitudinal Section of Rod ML at ~11.5 Inches from Bottom of Rod. (Note: Solid Hydride and Thick Oxide Near Outer Surface and Cracks Near Inner Surface)

791.6

100X

Figure 4-33. Transverse Section of Rod ML near Peak Heat Flux Region. (Note: Solid Hydride near Outer Surface and Cracks near Inner Surface of Cladding)

No heavily hydrided regions were observed in any of the seven sections from these two rods. However, several sections exhibited higher-than-normal hydrogen concentrations near the outer surface. One of these is shown in Figure 4-34.

Because of the suspect nature of fuel from pellet batch No. 3, archive rod MZ (which also contained batch No. 3 pellets) was characterized for internal gas content, moisture in the fuel, and hydrogen in both fuel and cladding. The rod was first punctured and the fill gas collected, the analysis of which revealed no evidence of hydrogenous contamination or other anomalous conditions. Moisture contents of individual pellets from the rod were determined with a CEC moisture analyzer. The results indicated an average of 2 ppm. Hydrogen analyses of archive cladding samples, both with and without autoclaving, assuming uniform and complete internal hydrogen pickup during autoclaving, showed that the initial moisture content of pellets in MZ was 12 ppm. Individual pellets also were analyzed for gaseous content. Because of low releases of volatiles, the hydrogen content of the pellets could not be measured directly. However, on the assumption that all gas evolved (after trapping the CO_2 and H_2O) is hydrogen, the equivalent average moisture content from this source is 3 ppm. Thus, pellet batch contamination by moisture or other hydrogenous impurity, as suggested by earlier observations (rods ML, MG, and MO), does not appear likely. The most probable cause of the observed hydriding is stray hydrogenous contamination introduced during fabrication.

FUEL MICROSTRUCTURE

The main features of the transverse fuel microstructures of pellet samples were (1) equiaxed grain growth in the center region out to about 0.7 of the pellet radius, (2) small, metallic precipitates in the area of grain growth usually in grain boundaries, and (3) clusters of gas bubbles around the original PuO_2 particles near the periphery of the fuel. These conditions are illustrated in Figure 4-35, which is a montage of the peak power transverse section from Rod QE. The extent of grain growth in these samples was greater than in the pellet fuel samples described in Section 4.2, indicating higher power densities and higher center temperatures. However, as with the earlier studies, none of the samples showed any central void or columnar grain growth.

804.1

100X

Figure 4-34. Transverse Section of Rod MO, 17.9 Inches from Bottom of Rod, Showing Heavier-than-Normal Hydriding

DISTANCE FROM EDGE OF FUEL, INCHES

Figure 4-35 FUEL MICROSTRUCTURE QF PEAK POWER
SECTION FROM ROD QE (AS POLISHED)

Center fuel temperature, although higher than that of previously examined Saxton $\text{PuO}_2\text{-UO}_2$ fuel, probably did not exceed 1700°C in any of the rods examined in this phase of the program. The metallic precipitates in the regions of grain growth have been noted in numerous other post-irradiation studies and are believed to be fission products.

Fuel structures for the highest power pellet rods (QE, TI, TE, TP, TT, and LA) were essentially the same, indicating similar thermal history. However, the peak power region from rod LA exhibited narrow, radially-oriented pores near the center of the sample, but no evidence of columnar grain growth, as shown in Figure 4-36.

The peak power section from the highest burnup vipac rod (K4) exhibited in-pile sintering from the center to about 80 percent of the fuel radius. Limited columnar grain growth was also evident on this sample, indicating higher center temperatures than on pellet rods of comparable burnup. These features are shown in Figure 4-37. The cladding structure on this sample appeared to be normal, with outer oxide film thicknesses equal to or less than those on pellet rods with similar power histories. As noted previously, most of the inner surfaces of the cladding had an oxide layer which varied in thickness from 0.1 to 0.4 mil. In many locations, fuel particles appeared to be bonded to the layer.

The two transverse sections of vipac rod K4 at 25 inches (grid contact area) and 30 inches from the bottom of the rod showed some of the same microstructural features seen on the peak power sample. However, the extent of grain growth and in-pile sintering was significantly less, which is as expected for these lower power samples. As with the peak power section, both samples exhibited significant oxide layers on the inner surface of the cladding, with apparent bonding of the fuel to the layer in numerous areas.

4.4.2.7 Hydrogen Analyses of Zircaloy Cladding

Twelve ring samples 32 determinations of Zircaloy cladding were removed from four fuel rods and were analyzed for hydrogen content by the vacuum hot extraction technique. The results, shown in Table 4-11, largely confirmed the estimated 70-100 ppm of hydrogen made from several photomicrographs of rod

693.38

250X

Figure 4-36. Fuel Microstructure Near Center of Peak Power Section of Rod LA

688.12-14

150X

Figure 4-37. Fuel Microstructure at Peak Power Region of Vipac Rod K4

TABLE 4-11

HYDROGEN IN IRRADIATED SAXTON CORE II FUEL CLADDING

Rod Number	Axial Location of Sample, in. ^(a)	Power Relative to Rod Peak	Hydrogen Content ^(b) , ppm
TI	17.6	1.00	76
TI	9.1	0.90	71
LA	17.6	1.00	80
LA	9.1	0.90	64
K4	17.6	1.00	51
K4	25.1	0.93	54
K4	30.1	0.75	66
K4	3.8	0.60	74
QE	17.8	1.00	93
QE	25.1	0.93	88
QE	30.1	0.75	71
QE	35.1	0.45	78

^aDistance from bottom of fuel rod.

^bBased on average of two or four determinations per ring sample.

QE cladding. Samples from vipac rod K4 had slightly lower hydrogen levels (51-74 ppm). The reason for the difference is probably the lower beginning-of-life hydrogen content of the tubing in rod K4. (The tubing lot used in the manufacture of vipac rod K4 contained an average of eight ppm hydrogen, compared with ~25 ppm for most of the pellet fuel tubes).

A series of tests on archive tubing showed that approximately 20 ppm of hydrogen was absorbed by the cladding during the 24-hour autoclaving run, which is one step in the processing of the fuel rods. Therefore, the beginning-of-life hydrogen contents for vipac and pellet fuel cladding were ~28 ppm and 45 ppm, respectively. Since the end-of-life hydrogen levels were 51-74 ppm and 64-93 ppm, the hydrogen absorbed during reactor operation was roughly the same for both types of rods, i.e., in the range of ~20 to 50 ppm.

4.4.2.8 Fast Flux Dosimetry

Six sets of cladding samples were analyzed for manganese-54 activity and iron content to determine fast flux exposure based on the iron-54 (n,p) manganese-54 reaction. These samples represented six different axial positions in the highest burnup rods from Saxton Core II. The manganese-54 activity measurements and the resulting fast fluence values are summarized in Table 4-12.

4.4.2.9 Mechanical Testing of Zircaloy Cladding

Zircaloy cladding for the plutonium region of Saxton Core II was made by cold tube reduction followed by a stress relief anneal at 1025°F for two hours to give a final cold work "equivalent" of ~10 percent. The pre-irradiation tensile properties are shown in Table 4-13. These indicate significant differences between the tubing lots used to make the pellet and vipac rods.

The post-irradiation tensile and burst specimens were prepared from various positions along the rods and were selected to provide material having as wide a range of fast neutron fluence and irradiation temperature as possible. Tensile specimens were six inches long while burst specimens were eight inches. Following fuel removal, the cut ends were carefully deburred to facilitate attachment of grips and pressure seals.

The tensile tests were run on specimens with a two inch gage length at a strain rate of 0.005 in./in./min. in accordance with ASTM-E-21. Straining was followed

TABLE 4-12

SUMMARY OF FAST FLUX DOSIMETRY, SAXTON CORE II FUEL CLADDING

Rod Number	Axial Location of Sample, (in.) ^a	Mn ⁵⁴ Activity, (dpm/gm of Iron)	Fluence (>1 Mev), (n/cm ²)
QE	25.1	5.17×10^7	2.8×10^{21}
QE	35.1	2.54×10^7	1.4×10^{21}
TT	1.9	3.15×10^7	1.7×10^{21}
TT	14.1	6.87×10^7	3.7×10^{21}
LA	9.1	5.27×10^7	2.9×10^{21}
LA	17.6	5.96×10^7	3.3×10^{21}

^aDistance from bottom of fuel rod

TABLE 4-13

PRE-IRRADIATION TENSILE DATA SAXTON CORE II TUBING

Tubing Lot Number	Type of Fuel Rod	Test Temperature, (°F)	Yield Stress, (psi)	Ultimate Stress, (psi)	Elongation, (percent)
2,3	Pellet	Room	65,100	89,300	24
2,3	Pellet	Room	66,400	89,600	22
1	Pellet	Room	65,500	90,000	21
1	Pellet	Room	66,800	90,200	23
2	Pellet	725	37,360	48,500	26
4	Vipac	Room	89,300	114,000	18
4	Vipac	Room	83,000	104,000	17

by an extensometer to beyond the 0.2 percent offset yield stress, after which the extensometer was removed and the test continued with time-base recording on an X-Y recorder.

The burst tests were made by pneumatic pressurization at a loading rate of 3000 psi/min. The specimens were loaded with ceramic pellets before testing to reduce the stored energy of the system. Diametral changes were recorded with an LVDT extensometer. These measurements, however, were often rendered inaccurate due to specimen bowing, and bulging of the tube to failure was invariably not at the location of the extensometer. Uniform and circumferential elongations were, therefore, determined from post-test measurements. Uniform elongation was approximated by determining the specimen diameter at locations remote from the bulged region. Justification for this is based on the assumption that once the point of plastic instability has been reached (that is, the tube is bulging), only small additional diameter changes occur in portions of the tube remote from the bulge. Failure strains were measured on selected samples using post-test metallography by sectioning the failed specimen at the transverse plane judged to be the position of maximum diametral extension. Measurements of the maximum circumference at failure were made from photomicrographs of the polished sections.

Test Results

A series of post-irradiation annealing tests was undertaken to define the maximum test temperature which ensured that no annealing of irradiation damage would occur during the test. The hardness data are shown in Table 4-14 and indicate that no annealing occurred up to 725°F. In order to allow an adequate margin of safety, the majority of tests were made at 675°F; two tensile tests were performed at 700°F.

As shown in Table 4-15, the tensile strengths ranged from 46,000 to 73,000 psi, with yield strengths of 40,000 to 67,000 psi, thus indicating modest irradiation strengthening. Correspondingly, the elongations of all samples were lower than those of non-irradiated cladding, but were sufficiently high to indicate generally ductile behavior (minimum of 2.5 percent uniform elongation and 6.0 percent total elongation). These elongations are significantly higher than for Zircaloy cladding irradiated in Yankee Core V, ^[18] probably because

TABLE 4-14

POST-IRRADIATION ANNEALING RESULTS FOR SAXTON CLADDING

Annealing Temperature, (°F)	Annealing Time (minutes)	Hardness DPH (Average of 6)
-	0	267
700	15	257
700	30	260
700	60	258
700	90	257
725	90	259
725	120	258
750	120	226

TABLE 4-15

TENSILE TEST RESULTS ON IRRADIATED SAXTON CORE II CLADDING

Sample Rod Number	Identification Axial Location, (Inches) ^a	Fluence (>1 Mev), (n/cm ²) ^b	Test Tempera- ture, (°F)	0.2% Yield Strength, (kpsi)	Ultimate Strength, (kpsi)	Uniform Elonga- tion, (percent)	Total Elonga- tion, (percent)	Reduction of Area, (percent)
TE	9.8-16.8	3.2×10^{21}	675	46.2	54.2	3.6	9.3	27
TI	3.0-9.0	2.3×10^{21}	675	54.2	61.7	5.2	9.3	48
TP	7.0-14.0	3.1×10^{21}	675	52.0	59.6	2.5	6.0	44
TT	2.0-8.0	2.3×10^{21}	675	49.1	57.9	6.0	11.3	31
TT	8.0-14.0	3.3×10^{21}	675	48.4	54.6	2.6	8.0	53
LA	3.0-9.0	2.3×10^{21}	675	48.4	58.1	7.1	15.1	50
LA	19.8-25.8	3.1×10^{21}	675	52.5	60.4	4.9	9.8	26
N1	8.0-14.0	3.1×10^{21}	675	51.6	64.8	5.6	18.4	46
N3	8.0-14.0	3.1×10^{21}	675	54.3	65.3	5.7	14.9	56
TE	2.0-8.8	2.1×10^{21}	675	67.0	73.1	2.9	12.2	48
JF	2.0-8.8	1.7×10^{21}	675	40.1	45.9	11.5	13.6	44
RI	2.8-8.8	2.0×10^{21}	675	56.9	65.9	6.1	19.5	53
S1	2.8-8.8	2.0×10^{21}	675	48.2	58.2	7.2	19.3	37
S1	9.8-16.8	3.2×10^{21}	675	56.7	67.8	3.6	7.9	37
P0	2.0-8.8	2.0×10^{21}	675	53.2	72.4	7.3	12.5	65
P0	9.8-16.8	3.2×10^{21}	675	42.3	62.0	3.5	11.1	67
P0	29.8-37.0	1.5×10^{21}	675	52.2	61.6	4.0	8.9	49
K4	30.3-36.5	1.8×10^{21}	675	48.3	52.0	3.3	10.4	64
N1	2.0-8.0	2.1×10^{21}	675	49.3	63.3	4.8	8.6	37
N3	2.0-8.0	2.1×10^{21}	675	45.8	59.2	4.1	10.1	58
TI	19.8-25.8	3.1×10^{21}	700	53.8	57.3	4.3	9.0	36
TP	1.0-7.0	1.9×10^{21}	700	44.8	53.8	4.2	18.2	60

^aDistance of specimen ends from bottom of rod.^bInterpolated fluence at center of sample, based on data in Table 4-13.

of higher average clad temperatures in Saxton Core II. Despite the fairly wide range of strengths and elongations, there was no apparent correlation of tensile properties with fast fluence and location within the core.

The burst test results are summarized in Table 4-16. The following points were considered in the evaluation of the data:

- a) Due to considerable bowing of the specimens during the test, a complete autographic record of the stress-strain curve to the yield stress was not possible. In order to overcome this difficulty, some specimens were tested containing internal steel mandrels. These enabled measurement of 0.2 percent yield stress, but the presence of the mandrel altered the failure mode to a shear-type "spiral" fracture.
- b) The stored energy release which occurred during specimen failure caused sufficient distortion in some specimens that sectioning to determine failure strain was not always possible, thus limiting the number of available failure strain measurements. Photographs of representative burst samples are shown in Figure 4-38.
- c) While most of the failure stresses fell within a reasonably narrow range, two values (N3 and TT) were low. Possible causes for these unexpected low values were (1) incorrect (too high) test temperature leading to annealing and (2) tube wall defects resulting from fuel removal. As a check on these possibilities, (1) microhardness readings were taken on selected samples in areas adjacent to the bulge and in the failed region, but they did not show evidence of significant annealing in the failed regions of the anomalous test samples; (2) metallographic examination showed several instances of mechanical damage to the cladding (reduced wall thickness). The damage, which probably occurred during removal of fuel from the samples, could have reduced burst pressures.

With the exception of the two samples noted above, the burst strengths (i.e., failure stresses) were approximately the same as the ultimate strengths of the tensile specimens. However, the uniform elongations in the burst tests were lower in all cases, which is consistent with the lower ductility expected in

TABLE 4-16

BURST TEST RESULTS ON IRRADIATED SAXTON CORE II CLADDING SAMPLES

Rod Number	Axial Location of Sample, Inches from Bottom	Fluence (> 1 Mev) (n/cm^2)	Elastic Modulus, (10^6 psi)	0.2% Yield Stress, (kpsi)	Failure Stress, (kpsi)	Uniform Elongation, (percent)	Failure Strain, (percent)
K4	9.5-17.5	3.3×10^{21}	12.2	49.0	76.6	0.8	6
LA	25.8-33.8	2.2×10^{21}	12.3	57.2	63.0	0.5	46
N1	21.0-29.0	3.2×10^{21}	13.0	N.D. ^a	76.3	1.0	--
N3	21.0-29.0	3.1×10^{21}	12.4	N.D.	38.5	0.8	--
TE	19.8-27.8	3.0×10^{21}	11.7	N.D.	58.9	1.3	13
TI	9.5-17.5	3.3×10^{21}	14.9	74.9	77.3	1.0	--
TI	25.8-33.8 ^b	2.2×10^{21}	10.4	73.9	74.7	0.9	2
TP	22.0-30.0	3.0×10^{21}	N.D.	N.D.	73.6	1.3	--
TT	20.5-28.5	3.4×10^{21}	9.4	N.D.	Leaked	0.7	--
TT	23.5-36.5	2.2×10^{21}	N.D.	N.D.	47.4	0.7	--

^aN.D. = Not determined^bTested with internal steel mandrel

Figure 4-38. Photographs of Typical (Top Two) and Non-Typical (Bottom) Burst Test Samples

biaxial test mode. The wide scatter in failure strains is partly attributable to the uncertainty in the metallographic measurements.

4.5 EXAMINATION OF FUEL RODS DURING RECONSTITUTION OF CORE III LOOSE LATTICE ASSEMBLIES

4.5.1 General

As part of the Saxton Extended Burnup Test program, over 300 rods were inspected prior to insertion into new "loose lattice" assemblies for further irradiation in the Saxton reactor as part of Core III. The objectives of the Extended Burnup Test (or Loose Lattice Program) are to:

1. Demonstrate performance capability of Zircaloy-clad mixed-oxide fuel elements over a broad spectrum of burnups and power levels.
2. Obtain depletion characteristics and transuranic isotope generation data for high burnup, mixed-oxide fuel.

Table 4-17 summarizes the power-burnup combinations of the rods which were to be irradiated in the seven loose lattice assemblies. It includes both beginning-of-life burnups and peak power densities, as anticipated at the time the loading plan for Core III was selected.

The inspections of the rods for the loose lattice assemblies consisted of the following:

1. Examination of most of the rods in the Mobile Fuel Evaluation System (MFES), which included three-screen television viewing, diameter scans with a hydrojet gaging system, and gamma scans with an ionization chamber.
2. Visual examination of 38 selected rods with the underwater periscope and single TV camera to evaluate crud deposits; two of these rods were sampled for crud.
3. Length measurements on 183 rods with an extended depth micrometer.
4. Supplemental diametral scans on approximately half of the rods with a portable LVDT-type profilometer.

TABLE 4-17

SUMMARY OF POWER RATINGS AND BURNUPS EXPECTED FOR
SAXTON CORE III LOOSE LATTICE FUEL

<u>Group Number</u>	<u>Nominal Peak Linear Heat Rating, kw/ft</u>	<u>Number of Rods</u>	<u>Peak Initial Burnup, MWD/MTM</u>	<u>Peak Expected EOL Burnup, MWD/MTM</u>
1 ^a	20	4	> 32,000	55,000
2	21.2-18.7	47	16,000-19,000	39,000-45,000
3	18.7-16.3	43	19,000-21,000	39,000-44,000
4	17.4-14.3	58	21,000-23,000	38,000-44,000
5	14.3-10.6	78	23,000-27,000	36,000-44,000
6	10.6-8.5	20	27,000-32,000	36,000-45,000

a. These four rods are in the center removable subassembly.

The major purpose of these examinations was to qualify rods for use in Core III, and to document the beginning-of-Core III-life conditions, particularly surface features, dimensions, and burnup distribution.

4.5.2 Visual Examinations for Crud Deposits

In the first phase of the crud evaluation, 14 rods were examined with the periscope and single TV camera. Generally, crud deposits were present on all rods, but they were much prominent on the higher power rods. There was evidence of only thin, (probably less than 0.001 in.), soot-like deposits on the low power rods. These visual examinations served as a basis for subsequent crud sampling of two of the fuel rods which appeared to have had sufficiently heavy deposits for meaningful thickness measurements and chemical analysis. Subsequent thickness measurements and sampling for density measurement were abortive because of equipment limitations. Radiochemical analyses showed that the crud was similar to that found on stainless steel clad rods.

Six removable rods from Core II 9 x 9 assemblies were examined to observe the nature and extent of crud deposits on low and intermediate burnup rods. Although in many areas the deposits appeared to have been rubbed or flaked off during handling operations, all of these rods exhibited light to moderate soot-like deposits. On two of the rods, there was no crud over about half the surface area; on the other rods, the crud was intact except for the four prominent axial scratches and appeared to cover the rods uniformly from top to bottom.

Later in the reconstitution program, 24 uncleaned rods were inspected to document their surface condition prior to their insertion into loose lattice assemblies. These 24 rods represented all power/burnup levels and, therefore, should have exhibited a wide range of surface conditions. Generally, the crud deposits were heavier on the Group 5 and 6 rods (rod average burnups of 15,500 to 21,000 MWD/MTM), as expected. These rods exhibited a variety of crud conditions, ranging from fairly thick (up to ~2 mils), patchy areas over the center 10 in. to a uniform brownish-gray, semilustrous surface. Frequently, there was evidence that crud was being scraped loose by the edge of the handling tool.

In the areas near grid contacts, crud patterns were generally altered and often appeared to be related to the perturbed flow. Near the ends (within ~ 3 in.) of the higher power rods, the surfaces appeared to be covered with a thin, grainy, non-lustrous dark gray film. Figure 4-39 shows the general appearance of the crud deposits in grid contact areas of a Group V fuel rod. It also illustrates the thin, non-lustrous film near the top end of the rod. The estimated crud thicknesses were less than 0.002 in., even in the areas with relatively heavy, patchy crud. Over the major fraction of the rod surfaces, the crud was probably less than 0.001 in. thick.

The lower burnup rods (Groups 2, 3, and 4) exhibited no patchy crud but showed the same grainy-type surface near the top and bottom ends as the high burnup rods. Near the grid contact areas, the surfaces were usually a non-lustrous, dark gray with similar swirl patterns as noted for Group 5 and 6 rods. The thicknesses of the crud on the lower burnup rods were estimated to be <0.001 inch.

The visual inspections of the crud evaluation rods also revealed the absence of clad cracks, swelling, hydride blisters, severe wear, and other defects. To minimize disturbance of the crud deposits, these rods were not characterized for dimensions prior to insertion into Core III assemblies. However, rods of equivalent power history were profilometer-scanned to help document the "beginning-of-Core III life" dimensions of each rod group.

The visual inspections in the MFES also revealed the expected axial scratches, about 90° apart, associated with removal of rods past the grids. Moreover, there was evidence of other bright scratches which exposed base metal. These are attributed to the multiple handling operations experienced by some of the rods. With the exception of the crud and scratches, the rods appeared uniformly black and lustrous, typical of Zircaloy-clad rods which had operated in a pressurized water reactor environment. Furthermore, none of the MFES visual examinations revealed any evidence of cracks, swelling, blisters, ridges, white corrosion products, or other obvious defects.

↑ TOP OF ROD

TOP GRID AREA OF ROD CI-8

↑ TOP OF ROD

CONTACT AREA NEAR SECOND-FROM-BOTTOM GRID OF ROD CI-8

Figure 4-39. Typical Appearance of Crud Deposits in Grid Contact Areas

4.5.3 Dimensional Measurements

4.5.3.1 *Length Changes*

Measurements of 183 fuel rods showed that all Zircaloy-clad rods increased in length by 0.13 to 0.24 percent. Table 4-18 summarizes the length change data taken on Zircaloy-clad rods during the reconstitution program. These data represent a sampling of measurements on at least seven rods from each burnup group. The results show a trend of greater length increases for the higher burnup rods; they also indicate less change in vipac rods than for pellet rods of comparable burnup. These length changes are consistent with the fast flux-related increases observed in Zircaloy tubing at other laboratories.^[19,20]

4.5.3.2 *Diameter Measurements*

The diametral scans with both the MFES and profilometer systems showed the following results:

1. Decreased rod diameters over most (approximately the center 30 in.) of the length of each rod as compared with diameters near top and bottom.
2. Mean diameters, expressed to the nearest 0.001 in., ranged from 0.388 to 0.393 in., as compared with pre-irradiation diameters of $0.392 \pm .002$ in.
3. In general, ovality was 0.001 to 0.002 in. but, in isolated instances, was as high as 0.006 in.
4. There was no evidence of gross fuel rod swelling and, with the exception of rod ML, no blisters.
5. There was occasional evidence of local clad ridging, up to ~ 0.0025 in., especially in higher burnup rods.

These results are generally consistent with the in-cell profilometry discussed in Section 4.4.2.3.

Early comparisons of hydrojet and profilometer data on the same fuel rods indicated that the two systems revealed similar trends, e.g., large ovalities or 1.5 to 2.5 mil ridge-type indications would appear at the same axial location

TABLE 4-18

SUMMARY OF LENGTH CHANGE DATA FROM SAXTON RECONSTITUTION PROGRAM

<u>Burnup Group No.</u>	<u>Type Fuel</u>	<u>Calculated Rod Average Burnup, MWD/MTM</u>	<u>Average Length Increase, %</u>	<u>Range of Length Increase, %</u>
2	Pellet	12,100	0.16	0.14-0.19
3	Pellet	13,100	0.18	0.17-0.19
4	Pellet	14,400	0.18	0.15-0.23
5	Pellet	16,400	0.18	0.15-0.22
5	Vipac	16,300	0.15	0.13-0.17
6	Pellet	19,500	0.21	0.19-0.23
1	Pellet	22,200	0.21	0.19-0.23

on the charts of both systems. Qualitatively, the comparisons were favorable; the quantitative comparisons, however, showed many inconsistencies. From a series of comparative scans on calibrated step standards and a premeasured drill rod, it was concluded that the portable profilometer provided better accuracy for the purposes of the reconstitution program and, therefore, was used as the primary means for measuring beginning-of-Core III-life diameters of the loose lattice rods. The hydrojet inspection performed a screening function, to help identify rods with local diameter variations. Such rods required specific analysis by the more accurate profilometer to assure compliance with acceptance criteria.

The major criteria for rejecting rods for use in the reconstituted assemblies were:

1. Cracks
2. Local collapse of clad in unsupported region
3. Longitudinal wrinkling
4. Blisters
5. Evidence of leaks

The visual and dimensional inspections and subsequent leak testing of reconstituted assemblies showed that none of the rods were rejectable on the basis of any of the criteria. The hydrojet data, however, identified several rods with anomalous dimensions, mainly ridge-type indications. The location and extent of these anomalous areas were confirmed by the portable profilometer.

4.5.4 Gamma Scanning

The gamma scans provided data on relative gamma activity, from which the end-of-Core II burnup distribution could be calculated. The results of the gamma scans also showed the burnup depressions associated with grid locations, particularly for the two center grids. Several rods exhibited apparent gaps in the fuel column. Three fuel rods which exhibited more prominent gap indications were not used in the loose lattice assemblies since there was no means of quantitatively determining the actual pellet separation from the gamma scan trace.

4.5.5 Leak Testing of Reconstituted Assemblies

Each of the seven reconstituted assemblies was leak tested by wet, dry, and a combination of wet and dry sipping techniques. These tests were designed to provide a positive indication of clad failure if the leakage was sufficiently great to yield detectable release of volatile or non-volatile radioactive chemical species. The release of radioactive material was facilitated by utilizing the decay heat in the fuel to generate pressure differences, thereby increasing the possibility of quick detection of a small leakage. The procedures consisted of collection and measurements of fission products released from either (1) fuel submerged in recirculating water, or (2) fuel partially submerged in stagnant water under various pressures, or (3) fuel allowed to heat up in a helium atmosphere at a controlled pressure.

These tests showed that there were no detectable leaks in any of the fuel rods in the reconstituted assemblies.

SECTION 5

CONCLUSIONS

The extensive examination of $\text{PuO}_2\text{-UO}_2$ fuel rods after irradiation in the Saxton reactor leads to the following conclusions:

1. Mixed-oxide fuel performed satisfactorily in Saxton Core II, with no evidence of fuel rod failures, thus confirming the adequacy of the design and fabrication procedures.
2. The fuel rods exhibited good dimensional stability, with a maximum of 0.23 percent length increase and, with the exception of one rod, maximum changes in mean diameter of 0.003 in.
3. Pellet and vibratory compacted fuel performed equally well, although length increases of vipac fuel were slightly less and center fuel temperatures in peak power vipac rods were somewhat higher than in highest power pellet fuel rods.
4. The cold-reduced and stress-relieved Zircaloy-4 cladding employed in the plutonium region of Saxton Core II performed well. Oxidation of its outer surface was highly variable and, in some areas, was greater than predicted from out-of-pile testing. Hydrogen uptake during operation was less than 50 ppm; resulting hydrides were randomly or circumferentially oriented. Mechanical tests of clad samples indicated moderate irradiation strengthening but retention of significant ductility (at least 2.5 percent uniform elongation as measured in tensile tests).
5. One fuel rod, which had anomalous dimensions, exhibited local massive hydriding but did not fail. The source of the excess hydrogen was probably stray contamination introduced during fabrication.

6. None of the changes in dimensions, microstructure, or properties indicate basic operational limits for $\text{PuO}_2\text{-UO}_2$ fuel in irradiation environments similar to those of Saxton Core II.

SECTION 6

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