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DIMENSIONAL CHANGES IN HIGH PERFORMANCE POWDER AND PELLET FUEL RODS PROFILOMETER STUDIES

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HIGH PERFORMANCE UO_2 PROGRAM

DIMENSIONAL CHANGES IN HIGH PERFORMANCE
POWDER AND PELLET FUEL RODS - PROFILOMETER STUDIES

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PREFACE

This report is the eighth in a series summarizing the results obtained during the High Performance UO_2 Program sponsored by the joint U.S. - EURATOM Research and Development Program. The entire report series constitutes the final summary report of the program and will be issued under the single report number GEAP-5100. Major technical topics in the final report will be designated by the sequence GEAP-5100-1 through 5100-11. The appendices, describing the individual pressurized water loop fuel assemblies irradiated, will follow the sequence GEAP-5100-A through 5100-M. These final reports and the earlier summary report (GEAP-4264) represent a comprehensive documentation of the experience and conclusions developed during the program at the Atomic Power Equipment Department of the General Electric Company. The final report topics and their corresponding report number designations are:

FINAL REPORT TOPICS

GEAP-5100-1	Pellet and Powder UO_2 Thermal Conductivity During Irradiation
GEAP-5100-2	Molten Fuel Rod Operation to High Burnup
GEAP-5100-4	Fission Product and Plutonium Redistribution in High Performance UO_2 Fuel Rods
GEAP-5100-5	Interaction of Iodine with Zircaloy-2. Out-of-Reactor Investigation of a Potential Cladding Failure Mechanism
GEAP-5100-6	The Thermal Conductivity of UO_2 by Direct In-Reactor Measurement
GEAP-5100-7	Beta-Gamma Autoradiographs of UO_2 - Variation with Thermal Performance and Decay Time
GEAP-5100-8	Dimensional Changes in High Performance Powder and Pellet Fuel Rods - Profilometer Studies
GEAP-5100-9	Mechanical Property Changes in Zircaloy-2, and Incoloy for Exposures to 2×10^{21} nvt (above 1 MeV)
GEAP-5100-10	Fission Gas Release from UO_2 Irradiated Isothermally

APPENDICES:

FUEL ASSEMBLY IRRADIATION REPORTS

GEAP-5100-A	EPT-6 Assembly
GEAP-5100-B	EPT-8 Assembly
GEAP-5100-C	EPT-10 Assembly
GEAP-5100-D	EPT-COM Assembly
GEAP-5100-E	EPT-12 Assembly
GEAP-5100-F	EPW-6/8 Assembly
GEAP-5100-G	EPW-6/8-A Assembly
GEAP-5100-H	EPW-6/8-V Assembly
GEAP-5100-I	EPW-10/12-V Assembly
GEAP-5100-J	EPW-12-V Assembly
GEAP-5100-K	EPT-12C-A Assembly
GEAP-5100-L	EPT-12C-B Assembly
GEAP-5100-M	EX-12A Assembly

GEAP-5100-3 and 5100-11 were planned originally as part of the final series but have since been eliminated on the basis that the topics intended for coverage by these reports are adequately covered in the other final topical and assembly irradiation reports. Their publication at this time would be redundant and impractical in terms of the available time and funds.

FOREWORD

"The United States and the European Atomic Energy Community (EURATOM), on May 27, 1958 and June 18, 1959, signed an agreement which provides a basis for cooperation in programs for the advancement of peaceful applications of atomic energy. This agreement, in part, provides for the establishment of a Joint US-EURATOM research and development program which is aimed at reactors to be constructed in Europe under the Joint Program.

"The work described in this report represents the Joint US-EURATOM effort which is in keeping with the spirit of cooperation in contributing to the common good by the sharing of scientific and technical information and minimizing the duplication of effort by the limited pool of technical talent available in western Europe and the United States."

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DIMENSIONAL CHANGES IN HIGH PERFORMANCE
POWDER AND PELLET FUEL RODS - PROFILOMETER STUDIES

J. P. Hoffmann
M. F. Lyons
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SUMMARY

The fuel rod dimensional data obtained during the High Performance UO₂ Program have been extensively analyzed and correlated. These data consist of detailed, pre- and post-irradiation micrometer measurements of the diameter and length of every rod irradiated and post-irradiation linear and spiral profilometer traces on selected rods representative of each of the fabrication variations tested.

The availability of both types of dimensional measurements on the same rods has provided a direct comparison of the two measurement techniques. The profilometer is a much more sensitive and accurate device and the data are more reproducible and less influenced by operator techniques than those from the micrometer. However, the profilometer measurement is more expensive and time consuming for a single rod examination because of the equipment set-up time.

The solid pellet fuel rod swelling data versus thermal performance level have been re-analyzed to determine the UO₂ phase change volume expansion with melting. The analysis is similar to that reported earlier⁽¹⁾ but the more accurate profilometer data, where available, are used and the measured fuel rod length changes are taken into account. The calculated phase change volume increase is 7.4% rather than the 7% reported earlier and is in slightly better agreement with the directly measured value of 9.6%.

A quantitative measurement of the severity of pellet interface ridging was developed with the number of ridges per rod and the mean ridge height as parameters. An analysis of the data with these parameters has confirmed the qualitative conclusions reported earlier regarding ridging, namely:

1. The ridging severity in a specific type of rod, i. e., solid pellet or hollow pellet, increases with increasing thermal performance.
2. The use of hollow pellets reduces ridging severity from that with solid pellets at equivalent thermal performance levels.
3. Ridging is essentially absent in compacted powder fuel rods although there are occasional nonperiodic disturbances in an otherwise smooth profile.

The individual ridge severity does not appear to increase beyond the onset of central melting and may actually decrease if over-all cladding swelling occurs. The observed maximum ridge height of about 2.5 mils in these rods is comparable to values measured in high performance rods operated below melting. No adverse effect of ridging on Zircaloy-2 clad performance was noted during these irradiations but the ridge sites are of concern as potential failure points from low cycle fatigue or other stress dependent failure mechanism.

One instance of what is believed to be incipient creep collapse of the Zircaloy-2 cladding was observed in a very high performance, high burnup rod. Detectable clad ovality developed over a substantial fraction of the high performance zone in this rod and suggests that cladding support by the pellets is reduced when operating with gross central melting.

I. INTRODUCTION

Extensive fuel rod dimensional data were obtained during the PWL irradiations in the General Electric Test Reactor (GETR) under the joint USAEC - EURATOM High Performance UO_2 Program.* Both micrometer and, subsequently, profilometer dimensional measurements were made on the irradiated rods and provided a direct comparison of the two techniques. These data are of considerable technological interest because they were obtained for a variety of fuel types, e.g., solid pellet, cored pellet, and compacted powder fuel over wide range of densities, and over a broad range of thermal performance levels, including values far beyond present commercial practice. As a result the influence of these parameters, i.e., fuel type and thermal performance, on UO_2 swelling and on the imposed cladding stress during operation can be determined.

As a benchmark in reviewing the dimensional data, the following calculation result is pertinent. Considering only simple uniform thermal expansion, and using appropriate expansion data for Zircaloy-2 and UO_2 at the PWL operating temperature, a 0.5 inch diameter UO_2 pellet will expand and elastically deform the clad at a heat flux of $\sim 400,000 \text{ Btu/h-ft}^2$, when the initial room temperature diametral gap is 0.006 inch. If the operating conditions are more severe, as in the High Performance UO_2 Program irradiations, plastic deformation of the cladding is predicted. In actual irradiations, nonuniform expansion mechanisms produce phenomenon, such as pellet ridging with even larger gaps and/or at lower thermal performance levels.

In this report, all the High Performance UO_2 Program fuel rod dimensional results are consolidated and the correlations and conclusions developed are given. The report is one of the series of final reports being prepared to cover specific topics that encompass the program as a whole, rather than being related to a single fuel assembly or single irradiation sequence. A complete list of the topics in the final report series has been given in the preface of this report.

II. IRRADIATION CONDITIONS

The irradiations were all performed in the Pressurized Water Loop (PWL) of the General Electric Test Reactor (GETR) with virtually identical irradiation hardware (Figure 1) and operating in essentially the same external coolant environment. The coolant conditions were:

Saturation Pressure	-	1000 to 1200 psia
Inlet Temperature	-	$\sim 345^\circ \text{F}$
Outlet Temperature	-	$\sim 370^\circ \text{F}$
Flow Velocity	-	16-34 ft/sec

III. FUEL ROD DESIGN AND FABRICATION

The test rods were nominally 39 inches long and contained about 34 inches of active fuel (Figure 2). The remaining internal free volume, which at times was increased by reducing the active fuel length, was provided for fission gas storage at the top of the rod. The Zircaloy cladding was 0.565 inch o.d. by 0.030 inch wall tubing. The pellet UO_2 was cold pressed and sintered and then centerless ground to provide a 0.006 ± 0.001 -inch gap in the cladding. Cored pellets were obtained by diamond burr drilling

* Contract No. At(04-3)-189, P.A. No. 17

Figure 1. Test Assembly Configuration

Figure 2. Test Fuel Rod Configuration

solid UO_2 pellets. The very high density powder fuel rods (90.5% dense) were fabricated by vibratory compacting selected particle size, arc-fused UO_2 into larger diameter tubing and then cold swaging to the final 0.565 inch o.d. dimension. Lower density powder rods were fabricated by straight vibratory compaction into 0.565 inch o.d. tubing. Prior to irradiation the fuel rods were extensively inspected including visual, 100% ultrasonic, complete x-ray, and mass spectrometer leak checking.

IV. IRRADIATION HISTORY

Forty-three fuel rods were irradiated during the High Performance UO_2 Programs as summarized in Table 1. A brief synopsis of the irradiation is given below to provide some perspective for the observed dimensional results. More detailed descriptions of the irradiations are available.⁽¹⁾ The correspondence between individual fuel rods and the assemblies in which they were irradiated can be determined from Table 1.

The first three fuel assemblies irradiated contained relatively high-density, solid pellet, fuel rods and were representative of the best design practice at the time. These three assemblies, EPT-6, EPT-8, and EPT-10 were irradiated in consecutive GETR cycles. The third assembly irradiation with EPT-10, was terminated prematurely by indications of a fuel rod failure and all three assemblies showed severe cladding swelling, sufficient to preclude continuation of the irradiations to higher thermal performance levels.

Evaluation of the problem, and especially supplementary capsule irradiation evidence, led to the conclusion that the most probable mechanism for the swelling was the occurrence of a significant UO_2 volume increase accompanying the solid-liquid phase change.* The primary evidence for this conclusion was:

1. The correspondence of the maximum swelling zone to the peak heat flux zone at startup;
2. The correspondence of the threshold thermal performance level for swelling with that required to initiate melting;
3. The apparent increase in swelling with thermal performance level;
4. The distinct axial expansion of the molten UO_2 fuel column in short length capsule irradiations.

Elements numbers 2 and 3 above are illustrated in Figure 3.** Almost simultaneously with the occurrence of fuel rod clad swelling during these irradiations, new measurements of the UO_2 volume change on melting were reported^(3,4) and they indicated a greater volume increase than previously suspected. Preliminary results suggested a value of 7% which was subsequently refined to 9.6%. Based on these results it became apparent that higher performance conditions could only be attained by devising a means to accommodate the increased fuel volume.

Two methods were given serious consideration for reducing fuel density to allow for the phase change volume increase:

1. Divide the present through rod design into capsule length segments and provide axial expansion areas within the molten fuel region and
2. Use hollow or dished pellets to provide the increased volume,

*Pre-irradiation evaluation of this potential problem indicated that a net volume increase on melting of the 95% TD pellets was improbable based on the then reported ~ 3% density decrease accompanying the phase change.

**See footnote, p. 48.

Figure 3. Volumetric Swelling of Various Fuel Types

TABLE 1. Fabrication and Irradiation Data

Assembly No. and Fuel Type	Rod Number	GETR Cycle	Pre - Irradiation Cladding Diameter (Inches)		Fuel Pellet-Clad Diametral Gap (mils)	Fuel Rod Length (Inches)	Fuel Column Length (Inches)	Max. Surface Heat Flux Btu/h-ft ²
			Outside	Inside				
EPT-6 Solid Pellets	6A	33	0.5647-0.5653	0.5058-0.5064	5.5	39.018	33-3/4	630,000
	6B		0.5642-0.5656	0.5060-0.5067	5.8	39.008	34-5/16	665,000
	6C		0.5611-0.5638	0.5064-0.5068	6.1	39.006	34-1/4	675,000
	6D		0.5642-0.5654	0.5051-0.5056	5.9	39.004	34-3/16	732,000
EPT-8 Solid Pellets	8A	33	0.5642-0.5652	0.5092-0.5106	6.4	39.014	34-1/4	950,000
	8B		0.5642-0.5668	0.5082-0.5091	5.1	39.020	34-9/32	920,000
	8C		0.5645-0.5663	0.5091-0.5100	6.0	39.031	34-3/16	780,000
	8D		0.5635-0.5648	0.5092-0.5100	6.1	39.032	34-1/4	915,000
EPT-10 Solid Pellets	10A	35	0.5671-0.5688	0.5093-0.5101	5.7	39.033	31-1/4	1,030,000
	10B		0.5675-0.5685	0.5094-0.5107	6.0	39.012	31-3/8	1,040,000
	10C		0.5663-0.5680	0.5100-0.5104	6.2	39.026	31-5/16	1,140,000
	10D		0.5668-0.5690	0.5097-0.5107	6.2	39.025	31-1/4	1,140,000
EPT-COM Small Cored Pellets	6E	37, 39	0.5647-0.5660	0.5046-0.5055	4.5	38.965	33-3/4	605,000
	8E		0.5635-0.5657	0.5092-0.5100	6.1	38.960	34	905,000
	10E		0.5679-0.5688	0.5098-0.5109	6.3	38.990	31-1/8	1,000,000
	12E		0.5685-0.5690	0.5108-0.5110	9.0	38.990	29-1/2	1,148,000
EPT-12C Large Cored Pellets	12AC	41, 42, 45	0.5620-0.5630	0.5001-0.5006	4.8	39.032	29-1/2	1,440,000
	12BC		0.5620-0.5630	0.5001-0.5018	5.4	39.036	29-1/2	1,360,000
	12CC		0.5610-0.5620	0.5000-0.5009	5.0	39.035	29-1/2	1,210,000
	12DC		0.5610-0.5630	0.5002-0.5009	5.0	39.045	29-3/4	1,255,000
EPT-12CA Large Cored Pellets	12BC	47	0.5620-0.5640	-	-	39.056	-	1,137,000
	12CC		0.5610-0.5630	-	-	39.069	-	1,107,000
	12GC		0.5610-0.5620	-	-	39.054	29-11/16	1,098,000
	12HC		0.5590-0.5605	-	-	39.051	29-5/8	960,000
EPT-12CB Large Cored Pellets	12CC	52	0.5600-0.5640	-	-	39.069	-	1,177,000
	12FC		-	-	-	-	29-11/16	1,230,000
	12HC		0.5590-0.5605	-	-	39.079	-	1,233,000
	12GC		0.5600-0.5630	-	-	39.062	-	1,061,000

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TABLE 1. (Continued)

Assembly No. and Fuel Type	Rod Number	GETR Cycle	Pre - Irradiation Cladding Diameter (Inches)		Powder Rod Densities	Fuel Rod Length (Inches)	Fuel Column Length (Inches)	Max. Surface Heat Flux Btu/h-ft ²
			Outside	Inside				
EPW-6/8 Vipac and Swaged Powder	6AA1	40	0.5654-0.5671	-	91%	39.034	34-1/8	531,000
	6AA4		0.5671-0.5682	-		38.924	34-1/8	536,000
	8AA2		0.5670-0.5695	-		39.067	34-1/8	721,000
	8AA4		0.5673-0.5695	-		39.992	34-1/8	615,000
EPW-6/8A Vipac and Swaged Powder 90%TD Vipac Powder	6AA1	40	0.565 -0.567	-	91%	39.026	-	642,000
	8AA4		0.5655-0.569	-	91%	38.990	-	744,000
	6AV		-	-	88%	-	34-1/8	648,000
	8AV		-	-	88%	-	34-1/8	872,000
EPW-6/8V Vipac Powder	6BV	43	0.5605-0.5620	-	86.33%	39.000	34-1/4	757,000
	6CV		0.5605-0.5620	-	86.90%	39.039	34-3/16	750,000
	8BV		0.5600-0.5610	-	87.39%	39.040	34-1/8	888,000
	8CV		0.5610-0.5620	-	88.86%	39.031	34-1/8	1,000,000
EPW-10/12V Vipac Powder	10AV	44	0.5620-0.5625	-	84.67%	39.017	34-1/4	1,210,000
	10BV		0.5610-0.5625	-	84.67%	39.010	34-1/4	1,107,000
	12AV		0.5600-0.5610	-	85.06%	38.970	29-1/2	1,482,000
	12BV		0.5615-0.5625	-	83.63%	38.943	29-1/2	1,351,000
EPW-12V Vipac Powder	12CV	47-52	0.5610-0.5625	-	83.83%	39.015	29-7/8	1,222,000
	12DV		0.5655-0.5665	-	85.00%	38.995	29-1/2	1,357,000
	12GV		0.5655-0.5660	-	83.00%	39.008	29-7/8	1,123,000
	12FV		0.5640-0.5650	-	84.97%	39.021	29-1/2	1,260,000
EX-12A Vipac Powder Large Cored Pellets (Liner)	12GV	54-58	0.5660-0.5680	-	-	39.027	-	1,070,000
	12FV		0.5640-0.5670	-	-	39.050	-	1,030,000
	12FC		-	-	-	-	-	1,360,000
	12KCF		-	-	-	-	-	1,170,000

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*There is approximately 10 percent variation in the heat flux values reported for the fuel rods from EPW-6/8 and EPW-6/8A in the various program reports. These variations arise from differences between physics and gamma scan indications of the power split among the rods and changes in the PWL axial peaking factors based on measurements performed midway through the program.

The use of hollow pellets was finally selected as the most straightforward approach. To evaluate this idea, a special assembly irradiation, designated EPT-COM, was performed with pellets cored with an 85-mil-diameter hole, equivalent to $\sim 3\%$ of the fuel volume. The pellets of these four rods were enriched such that a range of performance levels would be obtained. The irradiation of this assembly was performed in two steps, (1) a single short cycle of full power operation followed by examination and (2) a full cycle of irradiation with normal reactor power cycling. Post-irradiation examination revealed only slight swelling of one rod, Rod 10E, which occurred during the short cycle startup, with no indications of a ratcheting mechanism during the subsequent continued operation. However, because of the slight swelling of Rod 10E, it was concluded that the free volume provided by the small cored pellets was marginal for a performance level of 1.0×10^6 Btu/h-ft² and above, and a larger core was provided for the maximum thermal performance irradiation in the sintered pellet series, Assembly EPT-12C.

Assembly EPT-12C, to be irradiated at a nominal performance level of 1.2×10^6 Btu/h-ft² was provided with sintered pellets cored to an inside diameter of 0.140 inch. This larger core size was selected to provide about 8% (of the UO₂) free volume for the phase change expansion. To protect the rods further, a programmed startup procedure was introduced in the irradiations. This procedure was formulated in recognition of the significant axial fuel relocation observed in the previously irradiated rods and the possibility that the relocation could undo the initial benefit of the deliberately included central hole. The objective of the procedure was to prevent any sudden increases in internal volume without allowing time for axial redistribution. The reactor power rise rate was limited to less than 1 MW per 15-minute time increment and the restriction initiated at a power level below that at which the onset central melting would be expected. This startup procedure was specified for all startups following a reactor refueling, provided the predicted flux peak location was of 3 inches or more below that existing at the previous shutdown.* In the absence of a refueling resulting in a significant downward flux shift, no restriction on startup rate was made.

Irradiation of Assembly EPT-12C was successful through the first two reactor cycles to 5300 MWd/Te burnup with no detectable swelling of the rods, at performance levels as high as 1.4×10^6 Btu/h-ft². However, on the third cycle startup, rod swelling and one rod failure occurred. The unexpected result was subsequently traced to an inadvertent 4-MW step power increase before failure. Two of the rods from the EPT-12C assembly were only slightly swollen and continuation of their irradiation was attempted in two subsequent assemblies, EPT-12C-A and EPT-12C-B. However, both rods experienced pinhole type of failures during their initial startup or very shortly thereafter. No satisfactory explanation for the pinhole failures was obtained but some connection with the same event that caused the swelling and failure in the other two rods seems inescapable. New cored pellet rods, substantially identical to the EPT-12C rods, were fabricated later and operated satisfactorily to more than twice the EPT-12C assembly burnup in Assembly EX-12A.

Irradiations in the compacted powder UO₂ series were begun with 90.5% dense, vibratory-compacted and swaged rods in Assembly EPW-6/8. Because of the lower as-built density of these rods compared to solid pellets, they were expected to be less susceptible to swelling. Instead the powder rods showed greater swelling at equivalent thermal performance to the pellets, even with carefully programmed startups. This greater swelling was verified in a second assembly irradiation with 90.5% dense rods, EPW-6/8A. However, this same assembly also contained two 88% dense, straight, vibratory-compacted powder rods which demonstrated significantly reduced swelling at higher thermal performance than the

*GETR operation results in an axial flux peak shift as control rods are retracted to compensate for reactivity depletion during a reactor cycle. Refueling then results in an abrupt shift of the peak heat flux axial location.

two 90.5% dense rods. The effectiveness of reduced initial density in preventing swelling was confirmed in a third assembly containing straight, vibratory-compacted, 87 to 88% dense rods, EPW-6/8V. The concept demonstration was then extended to much higher thermal performance levels with the successful irradiation of 83 to 85% dense fuel rods at peak heat fluxes of 1.5×10^6 in a fourth powder assembly, EPW-10/12V.

On the basis of the above experience, the extended irradiation of the maximum thermal performance powder fuel assembly, EPW-12V, was undertaken and carried successfully beyond 10,000 MWd/Te average rod burnup at heat fluxes up to 1.3×10^6 Btu/h-ft². During the fifth GETR cycle of irradiation a fuel rod failure occurred which was subsequently traced to an initial fabrication defect. Very slight swelling was noted in the rods, which presumably occurred at the time of the initial startup. Two of the unfailed rods were then transferred to a new assembly with two new cored pellet rods. This assembly, EX-12A, was successfully irradiated for five more GETR reactor cycles at peak heat fluxes up to 1.4×10^6 Btu/h-ft² which brought the two powder rods to 20,000 MWd/Te average burnup and the two new pellet rods to about 12,000 MWd/Te. Extensive post-irradiation examination of these rods showed no further swelling in the powder rods, none in the pellet rods and no detectable deterioration of any kind. Coupled with the satisfactory irradiation performance, this assembly is considered to have demonstrated the intrinsic feasibility of high burnup operation with gross central melting.

V. DIMENSIONAL MEASUREMENT EQUIPMENT

The micrometer diameter measurements, both pre- and post-irradiation, were taken with the same tool, an ordinary 1-inch micrometer adapted for use in the hot cell. Pre-irradiation data were taken directly, out-of-cell. The micrometer adaptations for remote use consist of a stand to hold the micrometer upright, rather than flat, and a special spindle grip to facilitate turning the spindle with the hot-cell manipulators. The accuracy of the micrometer is considered to be that normally obtainable out-of-cell, i. e., ± 0.001 inch. However, the comparison of micrometer and profilometer results given in this report indicates there may be occasional less accurate values from the micrometer, probably because of the loss of a "sense of touch" in handling the micrometer remotely.

The profilometer is an integral unit designed for use in the hot cell and capable of measurements over a 4-ft-long rod. The basic diameter measurement is obtained with a pair of high-sensitivity, linear differential transformers. The transducers are mounted, opposed, on a cross head which can be moved axially the full length of the rod. The transducer probes bear on opposite sides of the rod to be measured and only the differential transducer signal is recorded to eliminate the influence of rod bowing. The fuel rod is gripped at each end in collets and can be rotated. A reference diameter standard is provided at one collet end to calibrate the profilometer at the start of every trace. The transducers can be moved parallel to the rod axis for a linear trace, the rod rotated for a circumferential trace, or the movements combined to yield a spiral trace which indicates the over-all rod ovality. The net output from the transducers is amplified and fed to the X-Axis input of an X-Y recorder. The Y axis is electrically coupled to the cross-head location on the rod. The profile traces are reproducible to less than 0.00025 inch and the absolute accuracy is also about ± 0.00025 when an accurate reference diameter is used.

The fuel rod length measurements were taken with a dial gage tool and a reference standard bar of accurately known length, approximately the length of the fuel rods. The length is determined by observing differences in dial gage readings on the standard and the unknown fuel rod and then algebraically adding the difference to the standard length. The accuracy of the length measurement is considered to be ± 0.004 inch provided appropriate temperature corrections are made and the rod is not appreciably bowed.

VI. DIMENSIONAL RESULTS

The dimensional data obtained from the PWL irradiations is presented in Tables 2 through 43. The majority of the data shown was obtained from micrometer measurements. Profilometer data, where available, has been superimposed on the micrometer data to provide a direct comparison of the two methods. Profilometer scans obtained on selected rods in three scanning modes, 0 degree, 90 degrees, and spiral traces, are presented in the Appendix.

VII. DATA ANALYSIS AND CORRELATION

A. Determination of the UO_2 Phase Change Volume Expansion from Cladding Swelling Data

Since the phase change expansion of the molten UO_2 is believed to be responsible for the observed, localized fuel clad swelling, it should be possible to calculate the magnitude of the expansion from the experimentally observed clad swelling to compare with the directly measured expansion value of (ΔV_{pc}) of 9.6%. An analysis to determine the expansion value was originally reported with a resultant value of 7%.⁽¹⁾ Essentially the same analysis has been reported here but with the more accurate dimensional data from the profilometer, where available, and taking into account the observed axial expansion of the rods.

The parameter used to represent the amount of swelling due to high performance operation of the fuel is the external change in rod volume. The calculation of this parameter is subject to the measurement errors already cited and is particularly sensitive to the inclusion or exclusion of the negative diameter changes observed with the micrometer and the rod length change. As discussed in Section VIII-A, the profilometer data do not show the same pattern of diameter decrease at the fuel column extremities which is apparent in the micrometer data. Furthermore, there is no recognized mechanism to induce this type of decrease at both ends* of the rod. The time, temperature and pressure are all insufficient in most cases to allow creep or other type of collapse. The negative diameter changes, therefore, are interpreted to be errors in measurement and are not reflected in the ΔV calculation.

The inclusion of the positive length changes in the calculated increase in rod external volume appears reasonable since the length increase undoubtedly occurs over the fueled zone. However, it must be recognized that the fuel rod length increase probably only partially represents the actual fuel column length increase depending on the size of the initial diametral gap. The fuel column above the point where the pellets lock to the cladding is free to expand into the upper spring-loaded plenum and would not be reflected in the external fuel rod length change. The positive length change, therefore, is considered to be a conservative, or lower limit, for the ΔV calculation. The few negative length changes are random and believed to be mostly from measurement errors (length measurement accuracy is estimated to be ± 0.004 inch except in a few specific cases, such as Rod 12AC, Assembly EPT-12C. In this case the rod

*A diameter decrease at the bottom of the fuel column could conceivably occur due to axial stretching of the cladding trapped between the locked peak heat flux location and the bottom end plug. However, this same effect would be impossible at the top where the fuel column is free to expand into the spring-loaded plenum area.

TABLE 2. ROD 6A

Station (Inches from Bot.)	Irradiation					
	0°			90°		
	Pre	Post*	ΔM (mils)	Pre	Post*	ΔM (mils)
3	0.565	0.565	0	0.565	0.564	-1
7	0.565	0.565	0	0.564	0.566	+2
11	0.564	0.566	+2	0.564	0.565	+1
15	0.564	0.564	0	0.564	0.564	0
19	0.564	0.564	0	0.564	0.563	-1
23	0.564	0.564	0	0.564	0.563	-2
35	0.565	0.565	0	0.565	0.563	-2
Length			+108			

*After operation at 630,000 Btu/h-ft²

TABLE 3. ROD 6B

Station (Inches from Bot.)	Irradiation							
	0°				90°			
	Pre	Post*	ΔM (mils)	ΔP^{**}	Pre	Post*	ΔM (mils)	ΔP^{**}
3	0.564	0.564	0	0	0.565	0.563	-1	0
7	0.564	0.570	+6	10	0.564	0.569	+5	8
11	0.564	0.567	+3	2	0.564	0.568	+4	1
15	0.564	0.564	0	0	0.564	0.564	0	0
19	0.563	0.564	+1	0	0.564	0.563	-1	0
23	0.564	0.563	-1	0	0.563	0.562	-1	0
35	0.564	0.563	-1	0	0.565	0.563	-2	0
Length			+137					

*After operation at 665,000 Btu/h-ft²

**Profilometer data assuming initial diameter 0.5650

TABLE 4. ROD 6C

Station (Inches from Bot.)	Irradiation					
	0°			90°		
	Pre	Post*	ΔM (mils)	Pre	Post*	ΔM (mils)
3	0.562	0.562	0	0.562	0.561	-1
5	-	63	2	-	64	3
7	1	78	17	1	75	14
9	-	0.605	44	-	0.605	44
11	1	0.564	3	0	0.554	4
15	0	2	2	0	51	1
19	0	0	0	0	59	-1
23	1	0	-1	1	61	0
35	3	1	-2	3	61	-2
Length			+80			

*After operation at 675,000 Btu/h-ft²

TABLE 5. ROD 6D

Station (Inches from Bot.)	Irradiation					
	0°			90°		
	Pre	Post*	ΔM (mils)	Pre	Post*	ΔM (mils)
3	0.564	0.564	0	0.564	0.563	-1
5	-	63	-1	-	64	0
7	4	72	8	4	73	9
8	-	0.610	47	-	0.611	47
9	-	0.579	16	-	0.581	17
11	3	67	4	4	68	4
15	3	4	1	4	5	1
19	3	3	0	4	3	-1
23	3	2	-1	3	2	-1
35	4	3	-1	5	3	-2
Length			+58			

*After operation at 732,000 Btu/h-ft²

TABLE 6. ROD 8A

Station (Inches from Bot.)	Irradiation					
	0°			90°		
	Pre	Post*	ΔM (mils)	Pre	Post*	ΔM (mils)
3	0.564	-	-	0.564	-	-
5	-	0.571	8	-	0.571	8
7	3	76	13	3	75	12
8	-	92	29	-	94	31
9	-	0.610	46	-	0.610	47
10	-	0.581	17	-	0.581	18
11	4	-	-	3	-	-
12	-	72	8	-	72	9
13	-	67	4	-	67	4
15	3	-	-	3	-	-
19	4	5	1	3	2	-1
23	3	2	-1	3	2	-1
35	4	3	-1	4	3	-1
Length			+57			

*After operation at 950,000 Btu/h-ft²

TABLE 7. ROD 8B

Station (Inches from Bot.)	Irradiation					90°		
	0°				ΔP^{**}			
	Pre	Post*	ΔM (mils)	ΔP^{**}		Pre	Post*	ΔM (mils)
3	0.565	0.565	0	0	0	0.564	0.565	1
4	-	66	1	0	0	-	65	1
5	-	66	2	0	0	-	65	1
6	-	67	3	1	2	-	70	6
7	4	72	8	1.5	3	4	70	6
8	-	75	11	3.5	6	-	76	12
9	-	83	19	6.5	8.5	-	85	22
10	-	81	17	11.5	8.5	-	81	18
11	4	88	24	12	10.5	3	91	28
12	-	79	15	12.5	5.5	-	78	15
13	-	71	7	6.5	1.5	-	67	4
14	-	68	4	2.5	0.5	-	6	3
15	4	66	2	1.5	0	3	4	1
19	3	63	0	0.5	0	3	3	0
23	4	63	-1	0	0	4	4	0
35	5	65	0	0	0	4	5	1
Length			+62					

*After operation at 920,000 Btu/h-ft²

**Profilometer data assuming initial diameter 0.56625

TABLE 8. ROD 8C

Station (Inches from Bot.)	Irradiation					
	0°			90°		
	Pre	Post*	ΔM (mils)	Pre	Post*	ΔM (mils)
3	0.565	0.564	-1	0.566	0.564	-2
4	-	-	-	-	5	0
5	-	4	-1	-	5	1
6	-	8	3	-	7	3
7	5	71	6	4	70	6
8	-	1	6	-	9	15
9	-	7	13	-	3	9
10	-	3	9	-	-	-
11	4	1	7	4	1	7
15	4	65	1	4	63	-1
19	4	3	-1	4	4	0
23	4	3	-1	5	3	-2
35	5	3	-2	6	3	-3
Length			+56			

*After operation at 780,000 Btu/h-ft²

TABLE 9. ROD 8D

Station (Inches from Bot.)	Irradiation					
	0°			90°		
	Pre	Post*	ΔM (mils)	Pre	Post*	ΔM (mils)
3	0.563	0.564	1	0.564	0.563	-1
4	-	5	2	-	3	0
5	-	7	4	-	4	1
6	-	5	2	-	7	4
7	3	71	8	3	73	10
8	-	3	10	-	76	13
9	-	83	20	-	80	17
10	-	0	17	-	78	15
11	3	3	20	3	81	18
15	3	64	1	3	63	0
19	3	4	1	3	67	4
23	3	2	-1	3	63	0
35	3	7	4	4	67	3
Length			+54			

*After operation at 915,000 Btu/h-ft²

TABLE 10. ROD 10A

Station (Inches from Bot.)	Irradiation							
	0°				90°			
	Pre	Post*	ΔM (mils)	ΔP^{**}	Pre	Post*	ΔM (mils)	ΔP^{**}
2	-	0.567	-1	0	-	0.568	0	0
3	0.568	68	0	0	0.568	69	1	0
4	-	70	2	1.5	-	71	3	1.5
5	-	75	7	2.5	-	76	8	4
6	-	89	2	16.5	-	96	28	9.5
7	8	0.615	47	21.5	8	0.615	47	24
8	-	0.609	41	24	-	0.609	41	24
9	-	0.580	12	11.5	-	0.578	10	10
10	-	75	7	7	-	75	7	5.5
11	8	81	13	7	8	80	12	6
12	-	78	10	6.5	-	77	9	6.5
13	-	6	9	5	-	5	8	5
14	-	3	6	4.5	-	3	6	3.5
15	7	0	3	3	7	1	4	3
19	7	66	-1	0	7	65	-2	0
23	8	6	-2	0	8	6	-2	0
35	8	7	-1	0	8	7	-1	0

*After operation at 1,030,000 Btu/h-ft²

**Profilometer data assuming initial diameter 0.5665. Reported profile data in error, numbers should be multiplied by 2 to correct for scan scale factor. (See section IX-A)

TABLE 11. ROD 10B

Station (Inches from Bot.)	Irradiation					
	0°			90°		
	Pre	Post*	ΔM (mils)	Pre	Post*	ΔM (mils)
1	-	0.565	-3	-	0.565	-3
2	-	8	0	-	6	-2
3	0.568	7	-1	0.568	8	0
4	-	8	0	-	9	1
5	-	73	6	-	74	6
6	-	95	28	-	95	27
7	7	0.627	60	8	0.624	56
8	-	0.617	50	-	0.616	48
9	-	0.586	18	-	0.587	19
10	-	79	11	-	81	13
11	8	92	24	8	94	26
12	-	90	22	-	92	24
13	-	82	14	-	81	13
14	-	77	9	-	75	7
15	8	72	4	8	71	3
19	7	65	-2	8	65	-3
23	7	6	-1	9	6	-3
35 (no fuel)	8	6	-2	8	5	-3
Length			+92			

*After operation at 1,040,000 Btu/h-ft²

TABLE 12. ROD 10C

Station (Inches from Bot.)	Irradiation					
	0°			90°		
	Pre	Post*	ΔM (mils)	Pre	Post*	ΔM (mils)
1	-	0.566	-2	-	0.565	-2
2	-	9	1	-	69	2
3	0.568	70	2	0.567	71	4
4	-	72	4	-	72	5
5	-	88	20	-	85	18
6	-	0.618	50	-	0.621	54
7	8	0.622	54	7	0.623	56
8	-	0.611	43	-	0.604	37
9	-	0.587	20	-	0.588	22
10	-	93	26	-	89	23
11	7	94	27	6	93	27
12	-	85	18	-	86	20
13	-	76	9	-	77	11
14	-	71	4	-	71	5
15	7	68	1	6	67	1
23	7	5	-1	6	6	0
35 (no fuel)	7	5	-2	7	5	-2
Length			+94			

*After operation at 1, 140, 000 Btu/h-ft²

TABLE 13. ROD 10D

Station (Inches from Bot.)	Irradiation					
	0°			90°		
	Pre	Post*	ΔM (mils)	Pre	Post*	ΔM (mils)
1	-	0.567	-1	-	0.566	-2
2	-	69	1	-	69	1
3	0.568	71	3	0.568	72	4
4	-	74	6	-	73	5
5	-	95	27	-	92	24
6	-	0.628	60	-	0.625	57
7	8	0.642	74	8	0.641	73
8	-	0.623	55	-	0.623	55
9	-	0.590	23	-	0.596	29
10	-	77	10	-	77	10
11	7	74	7	7	76	9
12	-	73	6	-	74	7
13	-	70	3	-	71	4
14	-	70	3	-	70	3
15	7	68	1	7	69	2
19	8	8	0	7	6	-1
23	8	6	-2	7	5	-2
35	9	6	-3	8	6	-2
Length			+54			

*After operation at 1,140,000 Btu/h-ft²

TABLE 14. ROD 6E

Station (Inches from Bot.)	Irradiation											
	0°						90°					
	Pre	Int	ΔM (mils)	Post*	ΔM (mils)	ΔP	Pre	Int	ΔM (mils)	Post*	ΔM (mils)	ΔP
3	0.565	0.565	0	0.564	-1	No Change	0.565	0.564	-1	0.563	-1	No Change
7	5	6	1	4	-2		5	4	-1	3	-1	
11	5	5	0	4	-1		5	4	-1	4	0	
15	5	4	-1	4	0		4	4	0	4	0	
19	4	4	0	3	-1		4	3	-1	3	0	
23	4	3	-1	2	-1		4	3	-1	3	0	
35	6	5	-1	2	-3		5	4	-1	2	-2	
Length			+24		+14							

*After operation at 605,000 Btu/h-ft²

TABLE 15. ROD 8E

Station (Inches from Bot.)	Irradiation											
	0°						90°					
	Pre	Int	ΔM (mils)	Post*	ΔM (mils)	ΔP	Pre	Int	ΔM (mils)	Post*	ΔM (mils)	ΔP
3	0.566	0.565	-	0.563	-2	No Change	No Data	0.563	-	0.563	0	No Change
7	Max.	3	-	3	0			5	-	4	-1	
11	Max.	2	-	3	1			4	-	3	-1	
15	Max.	2	-	2	0			2	-	3	1	
19	Max.	1	-	2	1			3	-	3	0	
23	Max.	3	-	4	1			3	-	4	1	
35	No Data	3	-	3	0			4	-	4	0	
Length			+10		+11							

*After operation at 905,000 Btu/h-ft²

TABLE 16. ROD 10E

Station (inches from Bot.)	Irradiation							
	0°				90°			
	Pre	Post*	ΔM (mils)	$\Delta P^\dagger$	Pre	Post*	ΔM (mils)	$\Delta P^\dagger$
3	No Data	0.567	0	0	No Data	0.566	-2	0
4	No Data	8	0	0	0.568 - 0.569	8	0	0
5	0.568 - 0.569	9	0	1	Max.	70	1	1
6	Max.	77	8	3.5	Max.	6	7	4
7	Max.	79	10	10	Max.	9	10	9
8	Max.	71	2	11.5	Max.	2	3	9
9	Max.	69	0	5	Max.	68	0	4
10	Max.	8	0	2	Max.	8	0	2
11	Max.	7	-1	2	Max.	7	-1	2
15	Max.	6	-2	0	Max.	6	-2	0
19	Max.	6	-2	0	Max.	6	-2	0
23	Max.	5	-3	0	Max.	5	-3	0
35 (no fuel)		6	-2	0		6	-2	0
Length			+52					

*After operation at 1,000,000 Btu/h-ft²

† Profilometer data assuming initial diameter 0.5677

TABLE 17. ROD 12E

Station (Inches from Bot.)	Irradiation									
	0°					90°				
	Pre	Int	ΔM (mils)	Post*	ΔM (mils)	Pre	Int	ΔM (mils)	Post*	ΔM (mils)
3	No Data	0.568	-	0.565	-3	No Data	0.567	-	0.566	-1
7	0.569 Max.	7	-	6	-1	0.569 Max.	7	-	5	-2
11	0.569 Max.	7	-	6	-1	0.569 Max.	7	-	6	-1
15	0.569 Max.	7	-	6	-1	0.569 Max.	7	-	5	-2
19	0.569 Max.	7	-	6	-1	0.569 Max.	7	-	6	-1
23	0.569 Max.	7	-	6	-1	0.569 Max.	6	-	6	0
35	0.569 Max.	6	-	5	-1	0.569 Max.	7	-	6	-1
Length			+11		+13					

*After operation at 1,148,000 Btu/h-ft²

TABLE 18. ROD 12AC

Station (Inches from Bot.)	Irradiation									
	0°					90°				
	Pre	Int	ΔM (mils)	Post*	ΔM (mils)	Pre	Int	ΔM (mils)	Post*	ΔM (mils)
3	0.563	0.563	0	0.566	3	0.562	0.563	1	0.562	-1
4	-	-	-	6	4	-	-	-	3	0
7	2	2	0	6	4	2	2	0	7	5
9	-	-	-	7	5	-	-	-	7	5
10	-	-	-	71	8	-	-	-	9	6
11	2	3	1	75	12	2	3	1	77	14
12	-	-	-	81	19	-	-	-	82	20
13	-	-	-	68	6	-	-	-	68	6
14	-	-	-	4	2	-	-	-	7	5
15	2	2	0	2	0	2	2	0	5	3
19	2	1	-1	2	1	2	2	0	2	0
23	2	1	-1	6	5	2	1	-1	4	3
35	3	4	1	3	1	2	2	0	4	2
Length			+56		-26					

*After operation at 1,440,000 Btu/h-ft²

TABLE 19. ROD 12BC

Station (Inches from Bot.)	Irradiation											
	0°						90°					
	Pre	Int	ΔM (mils)	Int	ΔM (mils)	Post*	Pre	Int	ΔM (mils)	Int	ΔM (mils)	Post*
3	0.563	0.563	0	0.563	0	0.563	0.563	0.564	1	0.563	-1	0.565
7	2	2	0	4	2	3	2	2	0	3	1	4
11	2	2	0	4	2	4	2	3	1	3	0	4
15	2	2	0	4	2	3	2	1	-1	3	2	4
19	2	2	0	3	1	2	2	2	0	3	1	3
23	2	2	0	3	1	2	2	2	0	4	2	2
35	2	2	0	3	0	2	3	2	-1	3	1	2
Length			+28		-8	-9						-1

*After operation at 1,360,000 Btu/h-ft²

TABLE 20. ROD 12CC

Station (Inches from Bot.)	Irradiation																	
	0°									90°								
	Pre	Int	ΔM* (mils)	Int	ΔM (mils)	Int	ΔM (mils)	Post	ΔM (mils)	Pre	Int	ΔM (mils)	Int	ΔM (mils)	Int	ΔM (mils)	Post	ΔM (mils)
3	0.562	0.563	1	0.563	0	0.563	0	No Data		0.562	0.562	0	0.562	0	0.562	0	No Data	
7	2	2	0	3	1	4	1	↓		2	2	0	2	0	3	1	↓	
11	2	2	0	2	0	2	0			1	1	0	2	1	3	1		
15	1	3	2	1	-2	0	-1			1	1	0	1	0	1	0		
19	1	1	0	2	1	1	-1			1	2	1	2	0	2	0		
23	1	1	0	1	0	2	1			1	2	1	1	-1	1	0		
35	2	2	0	2	0	2	0	↓		2	2	0	2	0	2	0	↓	
Length			+44		-7		-3											

*After operation at 1,210,000 Btu/h-ft²

TABLE 21. ROD 12DC

Station (Inches from Bot.)	Irradiation														
	0°										90°				
	Pre	Int	ΔM (mils)	Post*	ΔM (mils)	Pre	Int	ΔM (mils)	Post*	ΔM (mils)	Pre	Int	ΔM (mils)	Post*	ΔM (mils)
3	0.562	0.562	0	0.563	1	0.562	0.562	0	0.563	1					
6	-	-	-	4	2	-	-	-	2	0					
7	2	2	0	6	4	2	2	0	4	2					
8	-	-	-	3	1	-	-	-	3	1					
9	-	-	-	6	4	-	-	-	8	6					
10	-	-	-	77	15	-	-	-	77	15					
11	2	2	0	66	4	1	2	1	68	6					
12	-	-	-	8	6	-	-	-	8	6					
13	-	-	-	6	5	-	-	-	6	4					
14	-	-	-	5	4	-	-	-	5	3					
15	1	1	0	6	5	1	2	1	7	5					
19	2	2	0	2	0	2	2	0	1	-1					
23	2	1	-1	1	0	2	2	0	4	2					
35	3	2	-1	5	3	2	2	0	3	1					
Length			+58		-2										

*After operation at 1,255,000 Btu/h-ft²

TABLE 22. ROD 12GC

Station (Inches from Bot.)	Irradiation									
	0°					90°				
	Pre	Int*	ΔM (mils)	Post**	ΔM (mils)	Pre	Int*	ΔM (mils)	Post**	ΔM (mils)
3	0.562	0.561	-1	0.562	1	0.561	0.561	0	0.5610	0
7	2	1	-1	1	0	1	0	-1	10	1
11	2	1	-1	2	1	1	0	-1	15	1.5
15	2	2	0	1	-1	1	0	-1	10	1
19	2	1	-1	1	0	1	0	-1	10	1
23	2	3	1	1	-2	1	1	0	10	0
35	2	1	-1	1	0	1	1	0	10	0
Length			+12		No Data					

*After operation at 1,098,000 Btu/h-ft²

**After operation at 1,061,000 Btu/h-ft²

TABLE 23. ROD 12HC

Station (Inches from Bot.)	Irradiation									
	0°					90°				
	Pre	Int**	ΔM (mils)	Post*	ΔM (mils)	Pre	Int**	ΔM (mils)	Post*	ΔM (mils)
3	0.5600	0.561	1	0.5596	-1	0.5590	0.560	1	0.560	0
7	00	0	0	600	0	90	0	1	0	0
11	00	0	0	600	0	90	0	1	0	0
15	00	1	1	600	-1	90	0	1	0.5595	0
19	05	1	0.5	605	-0.5	90	0	1	600	0
23	00	1	1	600	-1	95	59	-0.5	0.5595	-1
35	05	0	-0.5	600	0	0.5600	59	-1.0	0.5590	0
Length			+28		No Data					

*After operation at 1,233,000 Btu/h-ft²

**After operation at 960,000 Btu/h-ft²

TABLE 24. ROD 12FC

(Inches from Bot.)	Irradiation											
	0°						90°					
	Pre	Int*	ΔM (mils)	Post**	ΔM (mils)	$\Delta P^\dagger$	Pre	Int*	ΔM (mils)	Post**	ΔM (mils)	$\Delta P^\dagger$
3	0.561	0.5605	-0.5	No Data		1	0.560	0.5600	0	No Data		2.5
7	1	10	0	↓		0	0	00	0	↓		1
11	1	10	0			1	0	10	1			-1
15	1	00	-1			0	0	05	0.5			0
19	1	10	0			1	0	00	0			-1
23	1	20	1			2	0	10	1			-2
35	2	20	0			2	1	05	-0.5			0.5
Length				No Data								

*After operation at 1,230,000 Btu/h-ft²

**After operation at 1,360,000 Btu/h-ft²

†After operation at 1,300,000 Btu/h-ft². Profilometer data assuming 0.561 initial diameter. Max. quality is shown on rotating profilometer trace.

TABLE 25. ROD 12FC

Station (Inches from Bot.)	Irradiation											
	0°						90°					
	Pre	Int	ΔM (mils)	Post*	ΔM (mils)	ΔP^{**}	Pre	Int	ΔM (mils)	Post*	ΔM (mils)	ΔP^{**}
3	0.566	0.567	1	0.566	0	0	0.565	0.565	0	0.565	0	0
5	-	-	-	6	0	1	-	-	-	5	0	0.5
7	6	6	0	8	2	1.5	6	7	1	7	0	1.5
9	-	-	-	9	3	2.5	-	-	-	9	3	4
10	-	-	-	76	10	5.5	-	-	-	74	8	5
11	6	7	1	3	6	6	6	7	1	75	8	5.5
12	-	-	-	-	-	3	-	-	-	-	-	2.5
13	-	-	-	68	2	2	-	-	-	67	1	1.5
14	-	-	-	-	-	1.5	-	-	-	-	-	1.5
15	6	6	0	6	0	1	6	7	1	6	-1	1
17	-	-	-	-	-	1	-	-	-	-	-	0
19	5	5	0	5	0	0	5	6	1	5	-1	0
23	7	7	0	7	0	0	7	7	0	6	-1	0
25	-	-	-	7	0	0	-	-	-	6	0	0
29	-	-	-	-	-	-	-	-	-	-	-	0
31	-	-	-	8	2	0	-	-	-	7	0	0
35	6	6	0	8	2	0	7	6	-1	8	2	0
Length			-8	No Data								

*After operation at 642,000 Btu/h-ft²

**Profilometer data assuming initial diameter of 0.5662

TABLE 26. ROD 6AA4

Station (inches from Bot.)	Irradiation					
	0°			90°		
	Pre	Post*	ΔM (mils)	Pre	Post*	ΔM (mils)
3	0.5670	0.566	0	0.5670	0.566	0
7	80	9	1	82	8	0
11	71	9	2	72	9	2
15	71	8	1	73	8	0
19	72	9	2	80	8	0
23	82	8	0	74	8	0
35	73	7	0	76	7	0
Length			-5			

*After operation at 536,000 Btu/h-ft²

TABLE 27. ROD 8AA2

Station (Inches from Bot.)	Irradiation					
	0°			90°		
	Pre	Post**	ΔM (mils)	Pre	Post**	ΔM (mils)
3	0.5685	0.567	-1	0.5673	0.565	-2
4	-	8	0	-	70	3
5	-	0.623	60	-	80	13
Defect*	-	36	-	-	76	-
6	-	0.565	-2	-	72	5
7	70	71	4	66	70	3
8	-	1	3	-	70	2
9	-	2	3	-	2	4
10	-	90	21	-	86	18
11	95	1	22	92	93	24
12	-	83	13	-	78	9
13	-	76	6	-	72	3
15	90	69	0	92	69	0
19	96	70	0	700	70	0
23	86	68	0	675	69	0
35	90	67	-2	85	68	0
Length			-16			

*Very localized burst at 5-inch elevation, one side only, ~ 1 inch long.

**After operation at 721,000 Btu/h-ft².

TABLE 28. ROD 8AA4

Station (Inches from Bot.)	Irradiation									
	0°					90°				
	Pre	Int*	ΔM (mils)	Post**	ΔM (mils)	Pre	Int*	ΔM (mils)	Post**	ΔM (mils)
3	0.5681	0.5655	-3	0.568	0	0.5692	0.5655	-4	0.569	0
5	-	-	-	71	1	-	-	-	71	2
7	93	90	0	3	4	0.5695	90	0	73	4
9	-	-	-	6	7	-	-	-	75	6
10	-	-	-	65	7	-	-	-	75	6
11	85	90	1	89	20	0.5673	90	2	94	25
12	-	-	-	0.638	69	-	-	-	0.646	76
13	-	-	-	21	52	-	-	-	0.6055	36
14	-	-	-	0.593	23	-	-	-	0.588	20
15	90	80	-1	84	16	0.5692	67	-2	0.5775	10
17	-	-	-	69	1	-	-	-	70	3
19	95	80	-1	68	0	94	65	-3	68	0
23	82	85	0	8	0	84	68	0	68	0
25	-	-	-	8	0	-	-	-	67	0
29	-	-	-	8	0	-	-	-	68	0
31	-	-	-	70	0	-	-	-	68	0
35	93	90	0	69	0	0.5690	69	0	0.5685	0
Length					No Data					

*After operation at 615,000 Btu/h-ft²**After operation at 744,000 Btu/h-ft²

TABLE 29. ROD 6AV

Station (Inches from Bot.)	Irradiation							
	0°				90°			
	Pre	Post*	ΔM (mils)	ΔP	Pre	Post*	ΔM (mils)	ΔP
3	0.563	0.561	-2	No	0.563	0.561	-2	No
7	2	1	-1	Change	2	1	-1	Change
11	2	05	-1		2	1	-1	
15	1	1	0		2	1	-1	
19	1	05	0		2	05	02	
23	2	1	-1		2	05	-1	
35	2	1	-1		2	1	-1	
Length			No Data					

*After operation at 648,000 Btu/h-ft²

TABLE 30. ROD 8AV

Station (Inches from Bot.)	Irradiation							
	0°				90°			
	Pre	Post*	ΔM (mils)	ΔP^{**}	Pre	Post*	ΔM (mils)	ΔP^{**}
3	0.563	0.561	-2	1	0.563	0.562	-1	1.5
7	2	1	-1	3	2	1	-1	2.5
11	2	0	-2	4	2	0	-2	4.5
15	2	59	-3	3.5	1	0	-1	3
19	2	60	-2	1.5	2	0	-2	1
23	2	2	0	0.5	1	1	0	0.5
35	3	3	0	0	2	3	+1	0
Length			No Data					

*After operation at 872,000 Btu/h-ft²

**Profilometer data assuming 0.563 initial diameter

TABLE 31. ROD 6BV

Station (Inches from Bot.)	Irradiation					
	0°			90°		
	Pre	Post*	ΔM (mils)	Pre	Post*	ΔM (mils)
3	0.5610	0.561	0	0.5605	0.5610	0
7	10	0.561	0	05	15	1
11	10	0.561	0	05	10	0
13	-	-	-	-	-	-
15	10	0.501	0	05	10	0
19	15	0.561	0	05	15	1
23	20	0.561	-1	05	10	0
35	15	0.561	0	10	10	0
Length			+19			

*After operation at 757,000 Btu/h-ft²

TABLE 32. ROD 6CV

Station (Inches from Bot.)	Irradiation					
	0°			90°		
	Pre	Post*	ΔM (mils)	Pre	Post*	ΔM (mils)
4	0.5610	0.5610	0	0.5610	0.5615	0
7	20	15	0	10	25	1
11	05	10	0	05	10	0
15	05	05	0	05	10	0
19	10	10	0	05	10	0
23	10	15	0	10	05	0
35	20	10	-1	15	10	0
Length			+19			

*After operation at 750,000 Btu/h-ft²

TABLE 33. ROD 8BV

Station (Inches from Bot.)	Irradiation					
	0°			90°		
	Pre	Post*	ΔM (mils)	Pre	Post*	ΔM (mils)
3	0.5605	0.5615	1	0.5600	0.5615	1.5
7	05	665	6	05	670	6.5
9	-	730	13	-	725	12
11	00	65	16.5	00	775	17.5
13	-	00	10	-	720	12
15	05	655	5	00	665	0.5
19	10	10	0	00	610	1
23	10	10	0	00	600	0
35	10	05	-05	00	605	0.5
Length			-24			

*After operation at 888,000 Btu/h-ft²

TABLE 34. ROD 8CV

Station (Inches from Bot.)	Irradiation					
	0°			90°		
	Pre	Post*	ΔM (mils)	Pre	Post*	ΔM (mils)
3	0.5610	0.5615	0.5	0.5620	0.5605	-1.5
7	10	40	3	20	60	4
9	-	65	5.5	-	55	3.5
11	10	90	8	20	700	8
13	-	75	6.5	-	680	6
15	10	40	3	20	35	1.5
19	10	30	2	20	20	0
23	10	10	0	20	10	-1
35	10	10	0	15	10	-5
Length			+4			

*After operation at 1,000,000 Btu/h-ft²

TABLE 35. ROD 10AV

Station (Inches from Bot.)	Irradiation							
	0°				90°			
	Pre	Post*	ΔM (mils)	ΔP^{**}	Pre	Post*	ΔM (mils)	ΔP^{**}
3	0.5625	0.5630	0.5	No	0.5625	0.5635	1	No
5	-	30	1	Change	-	35	1.5	Change
6	-	40	2	↓	-	45	2.5	↓
7	20	50	3		20	60	4	
8	-	40	3		-	00	4	
9	-	75	5.5		-	75	5.5	
10	-	85	6.5		-	80	6	
11	20	85	6.5		20	85	6.5	
12	-	85	6.5		-	85	6.5	
13	-	75	5.5		-	75	5.5	
14	-	70	5		-	75	5.5	
15	20	60	4		20	65	4.5	
16	-	50	3		-	50	3	
17	20	30	1		20	30	1	
23	20	30	1		20	30	1	
35	20	30	1		20	30	1	
Length			-12					

*After operation at 1,210,000 Btu/h-ft²

**

TABLE 36. ROD 10BV

(Inches from Bot.)	Irradiation					
	0°			90°		
	Pre	Post*	ΔM (mils)	Pre	Post*	ΔM (mils)
3	0.5625	0.5630	0.5	0.5625	0.5635	1
7	25	35	1	25	25	0
11	20	30	1	20	30	1
15	15	30	1.5	20	25	0.5
19	15	25	1	15	25	1
23	15	20	0.5	15	20	0.5
35	15	20	0.5	10	20	1
Length			5			

*After operation at 1, 107, 000 Btu/h-ft²

TABLE 37. ROD 12AV

Station (Inches from Bot)	Irradiation					
	0°			90°		
	Pre	Post*	ΔM (mils)	Pre	Post*	ΔM (mils)
3	0.5605	0.5610	0.5	0.5610	0.5610	0.5
7	05	20	1.5	05	20	1.5
8	-	30	2.5	-	30	2.5
9	-	40	3.5	-	40	3.5
10	-	55	5	-	60	5.5
11	05	70	6.5	05	70	6.5
12	-	85	8.0	-	80	7.5
13	-	80	7.5	-	80	7.5
14	-	60	5.5	-	60	5.5
15	05	55	5.0	05	35	3.0
16	-	20	1.5	-	15	1.0
17	-	20	1.5	-	10	0.5
19	05	-	-	05	-	-
23	05	10	0.5	00	05	0.5
35	05	10	0.5	05	10	0.5
Length			-8			

*After operation at 1, 482, 000 Btu/h-ft²

TABLE 38. ROD 12BV

Station (Inches from Bot.)	Irradiation					
	0°			90°		
	Pre	Post*	ΔM (mils)	Pre	Post*	ΔM (mils)
3	0.5620	0.5620	0.5	0.5625	0.5625	0
7	20	30	1.0	20	25	+0.5
11	20	30	1.0	20	25	0.5
15	20	15	-0.5	20	25	0.5
19	15	25	1.0	20	25	0.5
23	15	20	0.5	20	15	-0.5
35	20	20	0	20	20	0
Length			15			

*After operation at 1,351,000 Btu/h-ft²

TABLE 39. ROD 12CV

Station (Inches from Bot.)	Irradiation					
	0°			90°		
	Pre	Post*	ΔM (mils)	Pre	Post*	ΔM (mils)
3	0.5610	0.5630	2	0.5615	0.5630	1.5
7	10	30	2	20	40	2
10	-	40	3	-	50	3
11	10	50	4	15	50	3.5
15	15	50	3.5	15	50	3.5
19-1/2	-	30	1.0	-	30	1
19	20	30	1.0	20	30	1
23	15	30	1.5	20	20	0
35	25	30	0.5	20	30	1
Length			13			

*After operation at 1,222,000 Btu/h-ft²

TABLE 40. ROD 12DV

Station (Inches from Bot.)	Irradiation					
	0°			90°		
	Pre	Post*	ΔM (mils)	Pre	Post*	ΔM (mils)
3	0.5660	0.5670	1	0.5660	0.5670	1
7	60	80	2	60	90	3
9	-	730	7	-	730	7
10	-	750	9	-	740	8
11	60	50	9	60	60	10
12	-	60	11	-	60	10
13	-	60	11	-	50	9
14	-	50	9	-	50	9
15	65	00	4	60	25	6.5
16	-	20	6	-	20	6
17	-	10	5	-	10	5
18	-	10	5	-	20	6
19-1/2	-	680	2	-	680	2
19	60	80	2	60	80	2
23	60	60	0	60	60	0
35	65	60	0	60	60	0
Length			71			

*After operation at 1,357,000 Btu/h-ft²

TABLE 41. ROD 12GV

Station (Inches from Bot.)	Irradiation							
	0°				90°			
	Pre	Post*	ΔM (mils)	ΔP^{**}	Pre	Post*	ΔM (mils)	ΔP^{**}
3	0.5660	0.5660	0	0	0.5660	0.5660	0	0
7	60	60	0	1	60	60	0	1.5
10	-	70	0.5	2	-	60	0	2.0
11	65	70	0.5	2.5	60	70	1	2.5
15	65	70	0.5	2.5	65	80	1.5	2
19-1/2	-	70	1.0	2	-	65	0.5	0
19	60	60	0	0	60	60	0	1.5
23	60	60	0	0.5	60	60	0	1
35	60	60	0	0	60	60	0	0
Length			13					

*After operation at 1,123,000 Btu/h-ft²

**Profilometer data taken at 1,070,000 Btu/h-ft² assuming 0.5660 initial diameter.

TABLE 42. ROD 12FV

Station (Inches from Bot)	Irradiation							
	0°				90°			
	Pre	Post*	ΔM (mils)	ΔP^{**}	Pre	Post*	ΔM (mils)	ΔP^{**}
3	0.5645	0.5650	0.5	No	0.5650	0.5655	0.5	No
7	50	50	0	Change	50	45	-0.5	Change
10	-	50	0	↓	-	50	0.5	↓
11	40	40	0		40	40	0	
15	45	50	0.5		40	50	1	
19-1/2	-	70	2		-	50	0	
19	50	70	2		50	50	0	
23	45	55	1		50	50	0	
35	45	45	0		40	40	0	
Length			29					

*After operation at 1,260,000 Btu/h-ft²

**Profile data taken after second irradiation at 1,030,000 Btu/h-ft²

TABLE 43. ROD 12KCF

Station (Inches from Bot.)	Irradiation							
	0°				90°			
	Pre	Post*	ΔM (mils)	ΔP	Pre	Post*	ΔM (mils)	ΔP
3	0.566	No	No	No	0.566	No	No	No
7	6	Change	Data	Change	6	Change	Data	Change
11	6	↓	↓	↓	6	↓	↓	↓
15	6				6			
19	6				6			
23	6				6			
35	7				7			
Length			No Data					

*After operation at 1,170,000 Btu/h-ft²

was bowed sufficiently to account for the apparent length decrease. The phase change contribution to the total expansion can be found for each rod with the following expression:

$$\Delta V_{pc} = \Delta V_o + \Delta V_{tce} + \Delta V_{ece} + \Delta V_{fcl} \Delta V_{fcg} + \Delta V_{fav} - \Delta V_{tfe}$$

where

ΔV_{pc} = Volume Change - due to phase change

ΔV_o = Volume Change - externally observed

ΔV_{tce} = Volume Change - for the thermal expansion of the cladding

ΔV_{ece} = Volume Change - for the elastic expansion of the cladding

ΔV_{fcl} = Volume Change - from the fuel column expansion

ΔV_{fcg} = Volume Change - for filling the fuel-to-cladding gap

ΔV_{fav} = Volume Change - for filling the available internal fuel volume

ΔV_{tfe} = Volume Change - from fuel thermal expansion

The calculation shown above was made for each solid pellet rod in Assemblies EPT-6, -8, and -10. The following discussion of each of the ΔV contributions defines the assumptions made in each calculation.

1. Volumes Contributing to Swelling

- a. ΔV_{pc} - The volume change due to the solid-molten fuel phase change has been experimentally determined to be about 9.6%. This volume increase was calculated for each rod based on thermal performance levels.
- b. ΔV_{tfe} - Thermal expansion of the fuel is a factor which contributes to the magnitude of the swelling. It has been assumed here that 100% of the thermal expansion of that fuel which is molten is transmitted to the swelled area, and 50% of the thermal expansion of that fuel which is plastic, in the temperature range of 3,000 and 5,000°F, is transmitted to the swelled area. Thermal expansion of the outer shell of as-sintered fuel is also added for the length of the swelled region.

2. Volumes Receiving Swelling

- a. ΔV_o - The calculation of the observed volume change is made by using the dimensional data obtained by micrometer and profilometer measurements. These data are given in Tables 2 through 13 for each of the solid pellet rods. The calculated volume change determined by both types of measurements is given in Table 44. This radial volume change was calculated only over the axial zone with distinct swelling.

TABLE 44. Results of ΔV Calculations

Rod Number	Peak Life Heat Flux $\text{Btu/h-ft}^2 \times 10^{-5}$	Micrometer Measured ΔV_3 (in. ³)	Profilometer Measured $\Delta V(0^\circ/90^\circ)$ (in. ³)	Corrected Diameter ΔV_3 (in. ³)	Measured Length ΔV_3 (in. ³)	Total ΔV_3 (in. ³)
6A	6.30	.00887	-	.008	.0272	.035
6B	6.65	.03197	.0338/.0243	.030	.0350	.065
6C	6.75	.1263	-	.126	.0230	.149
6D	7.32	.0892	-	.089	.0170	.106
8A	9.50	.1457	-	.146	.0170	.163
8B	9.20	.1047	0.056/.0443	.050	.0170	.067
8C	7.80	.0490	-	.050	.0148	.065
8D	9.15	.1039	-	.104	.0143	.118
10A	10.30	.1653	.192/.194	.193	.0354	.228
10B	10.40	.2225	-	.223	.0284	.251
10C	11.40	.2519	-	.252	.0286	.271
10D	11.40	.2521	-	.252	.0175	.269
6E	6.05	0	0	0	.0100	.010
8E	9.05	0	0	0	.0052	.005
10E	10.00	.01827	.0339/.0310	.0325	.0137	.047
12E	11.48	0	-	0	.0061	.006
12AC	14.40	.0665	-	.0665	.0080	.074
12BC	13.60	-	-	-	0	-
12CC	12.10	0	0	0	0	0
12DC	12.55	.0494	-	.049	.01463	.066
12GC	10.98	0	-	0	0	0
12HC	12.33	0	-	0	0	0
12FC	12.30	0	0	0	0	0
6AA1	5.31	0	-	0	-	0
6AA1	6.42	.0253	.0248/.0236	.025	-	.025
6AA4	5.36	0	-	0	-	0
8AA2	7.21	.0968	-	.097	-	.097
8AA4	6.15	-	-	-	0	-
8AA4	7.44	.1911	-	.191	0	.191
6AV	6.48	0	0	0	-	0
8AV	8.72	0	.0481/.0444	.046	-	.046
6BV	7.57	0	-	0	.0047	.005
6CV	7.50	0	-	0	.0047	.005
8BV	8.88	.1079	-	.108	0	.108
8CV	10.00	.0489	-	.049	.0010	.050
10AV	12.10	.0514	0	0	0	0
10BV	11.07	0	-	0	.0012	.001
12AV	14.82	.0452	-	.045	0	.045
12BV	13.51	0	-	0	.0037	.004
12CV	12.22	.0362	-	.036	.0033	.039
12DV	13.57	.0842	-	.084	.0185	.102
12GV	11.23	0	-	0	.0030	.003
12GV	10.70	-	.0334/.0311	.032	.0073	.039
12FV	12.60	-	-	-	0	-
12FV	10.30	-	-	-	0	-

- b. ΔV_{tce} - The thermal expansion of the cladding is available to accommodate some of the fuel swelling. The volume change available was calculated using a temperature change from 75°F to 475°F and again only the distinctly swollen zone was included.
- c. ΔV_{ece} - The elastic cladding expansion is also available during irradiation to accommodate swelling but the post-irradiation measurements only show the plastic strain component remaining after relieving the cladding deforming force. The calculation was made using the 475°F yield strength of the cladding in the pre-irradiation condition. (The cladding should show no irradiation induced strength changes for the short operating time before the swelling event.)
- d. ΔV_{fcl} - The positive fuel rod length expansion is calculated from the measured length change and is considered to occur at the maximum swelled diameter (Section III-C-1).
- e. ΔV_{fcg} - The fuel-to-cladding diametral gap is an effective volume for accommodating fuel swelling. This volume is also calculated only over the region of distinct swelling.
- f. ΔV_{fav} - A portion of the fuel internal void volume is available to accommodate fuel swelling. It is assumed that the difference between the actual fuel density and the theoretical fuel density is completely available in the molten fuel and 50% available in the fuel that has some plasticity. As the fuel is assumed to transmit the swelling force, these volumes were calculated for the entire fuel column.

In other words, the following volume credits were taken:

1. For fuel at temperatures above 5,000°F (molten) - 5% available free volume
2. For fuel at temperatures between 3,000 and 5,000°F (plastic) - 2.5% available free volume
3. For fuel at temperatures below 3,000°F* (as-sintered) - 0% available free volume.

Each of these factors is given in Table 45 for all the rods considered and Figure 4 presents a plot of the calculated ΔV_{pc} data as a function of molten fuel volume (ΔV_m). The slope of a least square fit line through these data represents the phase change volume expansion, i.e., $\Delta V_{pc}/\Delta V_m$, and was determined to be 7.4%. A line corresponding to the directly measured phase change value of 9.6% $\Delta V_{pc}/\Delta V_m$ is also drawn on the plot for comparison. The data fit and correspondence in the two values is quite good considering the various rough approximations in the analysis, the accuracies of the fuel rod dimensional and thermal performance values, and the limited accuracy of the directly measured value itself, estimated to be about $\pm 30\%$.

The ΔV result for Rod 8B requires explanation, first because of its extremely low value and second, because this value is different from the value reported earlier⁽¹⁾ based on micrometer data alone. The new ΔV value is based on profilometer data and is a factor of 2 less than the micrometer based results (Table 7). There is a finite possibility that the profilometer scale factor was misrecorded during the measurements as is believed to be the case for Rod 10A (Table 10). However, the pellet ridging data

* 3000°F is a convenient temperature selection for analyses purposes and not intended to be interpreted as a judgment regarding the exact temperature for plasticity or grain growth in the UO_2 .

Figure 4. UO_2 Solid-Molten Phase Change Correlation

TABLE 45. ΔV Tabulation

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Rod Number	Peak H. F. at Startup Btu/h-ft ²	Fuel Volume Molten (in. ³)	Fuel Volume 3000-5000°F (in. ³)	ΔV _M (in. ³)	ΔV _P (in. ³)	ΔV _{FAV} 5+6 (in. ³)	ΔV _{FCG}	ΔV _{FCL}	ΔV _{ECE}	ΔV _{TCE}	ΔV _O	ΣΔV 7+8+9+ 10+11+12	Molten Pellet Swelled Area 70-3000°	ΔV Molten Fuel Whole Rod	ΔV Hollow Pellets 3000-5000°F Whole Rod	ΔV _{TFE} 14+15+16	ΔV _{PC} 13-17	ΔV _{PC} ($\frac{\%}{\Delta V_M}$)
6A	630,000	0.235	1.125	.012	.028	.040	.017	.026	.004	.002	.008	.097	.017	.0267	.045	.089	.008	3.4
6B	665,000	0.364	1.191	.018	.030	.048	.060	.035	.013	.009	.030	.195	.056	.041	.047	.144	.051	14.0
6C	675,000	0.389	1.199	.019	.030	.049	.063	.023	.013	.009	.126	.283	.056	.044	.048	.148	.135	35.0
6D	732,000	0.596	1.270	.030	.032	.062	.052	.016	.012	.007	.089	.238	.048	.068	.050	.166	.072	12.2
8A	950,000	1.439	1.349	.072	.034	.106	.072	.015	.015	.009	.146	.362	.060	.164	.054	.278	.084	5.8
8B	920,000	1.375	1.349	.069	.034	.103	.053	.016	.014	.009	.050	.244	.056	.156	.054	.266	-	-
8C	780,000	0.850	1.329	.043	.033	.076	.048	.015	.010	.007	.050	.206	.043	.097	.053	.196	.010	1.2
8D	915,000	1.342	1.347	.067	.034	.101	.073	.014	.015	.010	.104	.317	.065	.153	.054	.272	.045	3.3
10A	1,030,000	1.501	1.352	.075	.034	.109	.073	.035	.017	.012	.193	.439	.069	.171	.054	.294	.145	9.6
10B	1,040,000	1.518	1.356	.076	.034	.110	.077	.028	.017	.012	.223	.467	.069	.172	.054	.295	.172	11.3
10C	1,140,000	1.816	1.334	.091	.033	.124	.080	.029	.017	.012	.252	.514	.069	.206	.053	.328	.186	10.2
10D	1,140,000	1.821	1.334	.091	.033	.124	.080	.018	.017	.012	.252	.503	.069	.206	.053	.328	.175	9.62

appear normal at the indicated scale factor of 0.025 inch for full-scale reading. If the scale were actually 0.050 inch, then the pellet ridges would be ~4 mils high and larger than observed in any other rod. It is considered more likely that the true profilometer scale is 0.025 and the ΔV based on the profilometer trace is correct.

B. Pellet Interface Ridging

Ridging of the fuel cladding at pellet interface locations is a general characteristic of the fuel rods irradiated under the UO_2 High Performance Program and is similar to the circumferential ridging previously observed on fuel rods operated at thermal performance conditions below the UO_2 melting point.⁽⁸⁾ Although these ridges can at times be visually observed, their height and axial location can only be well defined by profilometer scanning. The profilometer scans, Appendix, Scan Sets 1 through 8, show the extent of pellet interface ridging from the various types of pellet fuel rods, over the spectrum of thermal performance conditions used in this program.

Evaluation of the circumferential markings observed on the profilometer scans demonstrates a direct correlation with pellet interface indications on the post-irradiation gamma activity profile. This correlation has been previously reported⁽⁵⁾ and is illustrated in Figure 5 for the PWL irradiations. For this rod (Rod 6B) there is a direct correlation over most of the length, between the axial position of the depressions on the gamma scan, indicating pellet interface locations, and the circumferential ridging on the profilometer scan. In the peak heat flux area the pellet interface indications have been obliterated from the gamma scan. This same axial zone, where the pellet interface locations are no longer visible on the gamma scan, coincides precisely with the area of swelling as defined by the profilometer trace. Either the pellets have become so fragmented in this zone from the UO_2 swelling that distinct pellet interfaces are no longer present or, simply, the fission product relocation associated with the more extensive grain growth and melting has masked over the interfaces. The gamma scan indications of pellet interfaces are also absent in later, higher performance rods where no swelling occurred, suggesting the fission product movement is the more significant factor. Since the pellet interface locations are clearly visible on the profilometer scans, it is probable that the ridging preceded the uniform swelling.

There is a strong influence of the type of fuel on the profilometer trace and, particularly, on the extent of ridging. Figure 6 provides a direct comparison of the profilometer scans from a solid pellet (Rod 6B), cored pellet (Rod 6E), and a powder rod (Rod 6AV). All three rods were irradiated at approximately the same thermal performance level. Qualitatively, the ridging is severe in the solid pellet rod, less severe and less extensive in the cored pellet rod, and totally absent in the powder rod. Analysis of the profilometer scans has provided quantitative measures of ridging severity which can be correlated to thermal performance level. The two measures of severity are the maximum ridge height and the mean ridge height which involves the number of detectable ridges per rod. In Table 46 these ridging parameters are given, as well as the increase in the maximum and mean ridge heights with increased thermal performance. Also evident in the table is the reduced ridging severity for equivalent thermal performance levels when using cored pellets. A further illustration of the correlation with thermal performance is the plot given in Figure 7 for Rod 6B. As can be seen, the ridge height increases as the peak heat flux zone is approached from either above and below the peak. As already mentioned, the ridge height is actually reduced in the localized, very highest thermal performance zone where the rod has experienced uniform swelling. However, there are still clear residual indications of ridging in this region.

Figure 5. Profilometer - Gamma Scan Correlation of Pellet Interfaces

Figure 6. Rod Profiles for Various Fuel Types

Figure 7. Ridging As a Function of Axial Location

TABLE 46. Pellet Interface Ridge Data

<u>Rod Number</u>	<u>Peak Heat Flux Btu/h-ft² × 10⁻⁵</u>	<u>Fuel Type</u>	<u>Maximum Ridge Height (Mils)</u>	<u>Mean Ridge Height (Mils)</u>	<u>% Visible Ridges (65 Pellet Base)</u>
6B	6.65	Solid Pellets	1.25	0.489	71
8B	9.20	Solid Pellets	2.15	0.766	69
10A	10.30	Solid Pellets	2.40	0.947	60
6E	6.05	Small Core	0.75	0.325	26
8E	9.05	Pellets	2.00	0.611	39
10E	10.00	Pellets	2.25	0.429	42
12FC	12.30	Large Core	1.60	0.807	79
12HC	12.33	Pellets	1.30	0.657	81

VIII. DISCUSSION OF RESULTS

A. Comparison of Micrometer and Profilometer Data

Examination of the tabulated dimensional data will show there are a number of discrepancies between the micrometer and profilometer data. The most significant examples are:

1. Almost all the fuel rods show a negative diameter change in the low power fuel rod section based on the micrometer measurements while the profilometer traces indicate no change from the pre-irradiation micrometer values.
2. Rod 10A shows approximately a factor of 2 greater swelling by micrometer measurement than from the profilometer scans.
3. Rod 8AV shows no swelling based on the micrometer measurements but the profilometer scan shows a definite diametral increase of + 0.005 inch.

In reconciling the above discrepancies, the following observations regarding the two measurement techniques are pertinent. The profilometer with its built-in diameter standard is inherently the more accurate device. In addition, the profilometer eliminates, to a large degree, the human element factors that are present in manipulating and reading the micrometer. Under direct measurement conditions, the micrometer has an accuracy capability of better than ± 0.001 inch but used remotely, the capability can be degraded in a number of ways. When the micrometer is manipulated with slaves, the tactile perception of perpendicularity is lost and there is a possibility of taking the data with the micrometer cocked. Thus, there may be a randomly occurring diameter values larger than actual. The micrometer is more difficult to read through the hot cell windows and periodic errors may occur from this cause. Finally, there are variations in operator technique that will bias the data. It is this last element that is believed to account for negative diameter change discrepancy noted above. With the loss of a "sense of touch" in performing the measurements, the natural tendency is to ensure micrometer contact by overtightening. With the mechanical advantage present in the small pitch micrometer threads, the diameter reading can be altered significantly. On the other hand, the bearing pressure of the profilometer probes is constant and determined by spring force rather than the operator. On this basis, the post-irradiation profilometer data indicating no negative diameter changes is considered correct.

Similarly, the profilometer data indicating a diameter increase in Rod 8A is believed to be correct rather than the micrometer data which shows a slight decrease. In this case, the decision is related to the inherent advantage of the profilometer in providing a continuous trace. No matter what the absolute accuracy of the trace calibration, the fact that a change in diameter has occurred is obvious and its location is consistent with more pronounced swelling in other rods. In contrast, it is quite easy to make a mistake of 5 mils in reading a micrometer, particularly in the midst of a series of discrete measurements that are nearly identical.

The one instance where the profilometer data are believed incorrect is Rod 10A where the profilometer measured swelling is only one-half that determined by micrometer. If the profilometer results were correct the swelling in Rod 10A would be totally inconsistent with the other three rods in assembly EPT-10. For this reason, it seems more likely that the scale factor of 0.025 inch recorded on the profilometer chart was a mistake. If the scale factor was 0.050 inch full scale instead of 0.025 inch, the profilometer data would correspond very closely to the micrometer data. An exact factor of two errors in the profilometer data is probably the most likely error considering its characteristics but the same factor error with the micrometer would be an exception rather than a general rule. This potential source of error in the profilometer data can be easily eliminated by making the scale factor setting be automatically recorded on the data chart.

Although the profilometer is more expensive and time consuming than the micrometer for a single rod measurement because of the equipment setup time, the quality and accuracy of the resultant data more than compensates. The actual time consumed in rod measurement is equal to or less than with the micrometer, and if the several rods are to be measured consecutively, as was the case here, the extra time and expense with the profilometer, if any, is insignificant.

B. Pellet Ridging

The circumferential ridging which has occurred on these PWL pellet fuel rods is quite similar to that observed in fuel rods operated below the onset of melting.⁽⁵⁾ It does not appear that the molten fuel rod operation has aggravated the ridging condition and in the swollen areas has actually partially wiped out the ridges. Theoretical analysis of the ridging phenomenon has suggested thermal stresses in the pellets as the most probable explanation. The pellets naturally tend to assume an hour-glass shape when subjected to the effects of the thermal gradient. In some cases ridging is observed at locations in between the pellet interfaces. In these instances it is believed that the pellets have cracked transversely and are acting as two pellets. The effect of the fuel pellet-to-clad gap on the occurrence of pellet interface ridging is interrelated with the thermal performance level. When the performance level is low enough so that fuel pellet cladding differential expansion is insufficient to close the gap, ridging does not occur. This is best demonstrated at the top of the rods where the heat flux is low and no ridging is observed. The extent of clad ridging over cored pellets is reduced from that with solid pellets. The hollow pellet apparently affects the hour-glass expansion characteristic of the cylindrical body in some manner not completely understood.

C. Clad Swelling Observations

Examination of the dimensional data shows a tendency of the swelling to be somewhat random in occurrence and severity. One example is the swelling of Rod 10E and not of 12E, although 12E was operated at higher power. The occurrence of the double peak in some of the rods also suggests a randomness in swelling although an alternate explanation for the appearance of double peak is offered later. These anomalies could be explained by differences in the axial expansion restraint of each type fuel as a result of interaction with the cladding. In the case of pellet fuel, either solid or cored design, the size of pellet-to-cladding gap may be significant. A large gap would allow axial movement of the fuel column above the molten region into the spring loaded plenum area. As previously noted, the fuel below the molten region is trapped between the locked peak power location and the bottom end plug and axial expansion of the nonplastic shell could conceivably stretch the cladding. As can be seen in Table 1, Rod 12E, which operated at 15% greater power than Rod 10E but showed no swelling, also has 42% larger diametral gap. It is postulated that this larger gap allowed the molten fuel in Rod 12E to expand the fuel column axially and accommodate the phase change swelling. Also to be noted is the factor-of four greater length change in Rod 10E which is again consistent with the contention that the fuel column in Rod 12E had freedom to expand within the clad.

In the swaged and vibratory compacted powder fuel, where there is no fuel-to-cladding gap, there must be a similar effect of fuel particle-cladding gripping. The degree of axial and circumferential deformation of the cladding as a result of fuel column movement restraint, i. e., locking of the molten fuel zone to prevent axial expansion, is undoubtedly a function of the fuel density. Thus, the density of the compact can then not only affect the degree of swelling directly because of the included volume for accommodation of expansion, but also indirectly by the degree of restraint of axial fuel column movement.*

*A small axial shift of the fuel column provides a relatively large expansion volume.

This combined action may account for the very large difference in performance with fuel density between the vibratory compacted powder fuel rods in Assemblies 6/8A, 6/8V and those in 10/12V. The rods in Assemblies 6/8A and 6/8V contained fuel compacted to 88% TD and general swelling occurred in all rods operated above 800,000 Btu/h-ft². The rods in Assembly 10/12V contained fuel compacted to only 83% TD and no swelling was observed at heat fluxes greater than 1,200,000 Btu/h-ft².

The degree to which each of the modes of swelling accommodation interact is difficult to assess in any more than general terms. In this regard, it is of interest to compare the relative initial free volumes which are available at any rod cross section for the different fuel types tested.

<u>Fuel Type</u>	<u>Total Free Volume**</u>
Solid Pellets	8%
Small Cored Pellets	11%
Large Cored Pellets	16%
Swaged Powder	10%
Vipak Powder (88% TD)	12%
Vipak Powder (83% TD)	17%

**Includes fuel density, gap, and core where provided.

It is apparent that the swaged powder fuel is not much better than the solid pellets and not as good as the small core pellets in terms of free volume to accommodate swelling. However, the difference in total free volume between the swaged fuel and the small core pellets is small and in no way compares to the large difference in swelling for these two types. On the other hand, when the severe fuel-to-cladding contact characteristic of the compacted and swaged fuel is considered, it is no longer surprising that the worst cases of swelling were encountered with this type of fuel. The initial contact and actual interference between fuel and cladding probably preclude any axial fuel column movement whatsoever. Coupled with the lower thermal conductivity and reduced availability of the uniformly distributed free volume in the powder fuel, this fuel type is, in retrospect, by far the most susceptible to swelling. The initially disproportionate appearing swelling in Rods 8AA2 and 8AA4 is readily understandable when viewed in light of the suggested role of cladding restraint on axial fuel column motion. In Rods 8AA2 and 8AA4, actual cladding failure occurred due to the severe swelling at the peak heat flux locations.

The markedly reduced swelling in 85% TD, vibratory compacted powder fuel rods probably relates mostly to the larger included free volume to accommodate phase change expansion. But in addition, an indirect contribution may be present from the fuel-to-cladding contact force being reduced to the point where some fuel column axial displacement is possible. However, the possibility of axial fuel column movement may also be related to the individual cladding and fuel particle characteristics. In-reactor fuel sintering could improve the axial expansion possibility if it occurred before the phase-change-induced swelling event. Conversely, a randomly located large fuel particle or localized areas of greater density could grip the cladding. Localized variations in UO₂ density acting in this manner could account for the more random occurrence and magnitude of swelling in the Vipak powder fuel rods.

The unbroken pattern of very localized swelling at the peak heat flux location at startup leads to the conclusion that the swelling occurred at the initial rise to power. However, the fact that with gross melting, the swelling remains localized instead of spreading out over the entire molten length of the rod requires further explanation. In this case, it is postulated that the peak heat flux location swells first because it is the area where first elastic and then plastic strain occurs during the rise to power. This may or may not occur before the melting event depending on the cold fuel-to-cladding gap. However, when it does occur, this area will have a larger diameter and hence will be the area of greater stress by virtue of the (Pr/t) relationship. This coupled with the smaller increment of stress required to continue plastic strain and the decreased wall thickness due to yielding of the cladding makes a very effective concentration factor. The molten fuel will then act as a hydraulic fluid to transmit the increasing pressure from the entire molten zone to the weakened area.

As already noted, double peaks in some rods may be the result of variations in the amount of restraint of axial fuel column movement. Alternatively, the occurrence of the double peak may be the result of swelling subsequent to the initial startup after the internal free volume of the rod has been redistributed by axial fuel movement. Nominally, this could occur on the rise to power after a mid-cycle shutdown when the peak heat flux location had shifted upward. The observed second swelling peak is generally smaller and between 2 and 5 inches above the first. It is felt that the second peak is a result of phase change expansion when both the central void and previous swollen areas are isolated by solidified molten fuel. The programmed startup procedure, instituted to prevent this occurrence, seems to have been successful since no double peak observations were made after irradiations in which this technique was used. The programmed startup procedure allows time for the molten fuel to melt into the central void region by plastic deformation of the solid UO_2 plug. Without the programmed startup, the molten zone could expand quite rapidly and deform the cladding before pressure relief by the molten zone reaching the central void region. The programmed startup was established specifically for GETR operations, with its shifting peak heat flux characteristic. The need for this precaution in reactors with more stable axial flux profile is uncertain.

D. Comparison of Phase-Change-Induced Swelling in Powder and Pellet Fuel

The correlation between thermal performance level and the amount of localized swelling was recognized early in the irradiation program and steps to relieve the swelling were taken by reducing the fuel bulk density. The swelling data as a function of thermal performance for all the fuel rods irradiated are presented in Table 44 and Figure 3. Based on a least square fit of the data, the following slopes were determined for the two fuel types where swelling was uncompensated by deliberate density reductions, i. e. solid pellet and swaged powder.

Solid pellet	- 1.12
Swaged powder	- 1.85*

As can be seen, the swaged-powder rods show a much steeper slope for swelling with increasing thermal performance. However, the lower limit for the onset of swelling in both the swaged powder and solid pellet rods is about the same and close to the expected thermal performance level for the onset of melting in pellet fuel. The onset of melting in powder fuel is believed to occur at a substantially lower thermal performance level so the extra internal free volume in the case of powder appears to be effective in delaying external volume changes until substantial UO_2 melting has occurred. Once the extra volume is exhausted, however, the powder rods swell more rapidly with increasing thermal performance level.

*The indicated curve and slope for swaged powder fuel was determined including the three data points on the abscissa, i. e., rods in which no swelling actually occurred. Considering only the three data points where swelling was observed the curve becomes even steeper and the onset of swelling is displaced to higher performance levels than for pellet fuel.

E. Zircaloy-2 Creep Collapse

What is believed to be the start of creep collapse of a nominally free-standing Zircaloy-2-clad tube was observed in one rod after long-term operation. Rod 12FC was irradiated for 2450 hours at 1200 psi external pressure with an average cladding temperature of 470°F. As can be seen from the pre- and post-micrometer measurements, Table 24, and the post-irradiation profilometer scan, Appendix, Scan Set 8, the rod has deflected to a maximum of 6 mils ovality in the area between 12 and 15 inches from the bottom. The oval zone extends over a large fraction of the high performance section of the fuel rod including the peak heat flux location during the majority of each reactor cycle. It is interesting to note that pellet interface ridging is evident in both the 0 and 90 degree orientation scans over this same span. If strong pellet support, as evidenced by the pellet ridges, existed throughout the irradiation creep collapse could not have occurred. The obvious conclusion is that at some point in the irradiation, the cored pellets have ceased to support the cladding. It seems likely that the pellet ridging occurs primarily during the startup to full power when the pellets are unmelted and relatively rigid bodies. This is consistent with the observation that the maximum ridging in these very high performance rods is not significantly different from that observed at conventional thermal performance levels. Once the core of the rod begins to melt, the UO_2 forces exerted on the clad no longer increases and probably actually decreases as the control molten zone becomes very large. Once this internal support is lost, the opportunity for unstable cladding behavior exists.

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APPENDIX

PROFILOMETER SCANS

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