135' Fast Reactor
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MASTER

AXIAL EXPANSION OF MIXED-OXIDE FUEL MEASURED IN-PILE

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U. S. ATOMIC ENERGY COMMISSION
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**AXIAL EXPANSION OF MIXED-OXIDE FUEL
MEASURED IN-PILE**

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ABSTRACT

The effect of power changes and burnup on the axial length of a $(\text{Pu}_{0.25}, \text{U}_{0.75})\text{O}_{1.98}$ fuel column irradiated at power levels between 5 and 17 kW/ft to burnups of 44,000 MWd/Te were measured in reactor as a continuous function of time. The expansion of the fuel was always less than the value computed based on fuel center temperature. After the as-fabricated fuel-cladding gap was closed (after a burnup of $\sim 20,000$ MWd/Te) the measurements of fuel column expansion were erratic and unpredictable.

1. SUMMARY

An experiment was conducted in-pile to determine the axial expansion of a 10-inch column of mixed-oxide fuel, $(\text{Pu}_{0.25}, \text{U}_{0.75})\text{O}_{1.98}$, with an initial fuel-to-cladding diametral gap of 0.005 inch. Relative movement between fuel and cladding was monitored as a function of power and burnup up to 44,000 MWd/Te (274 days) by a continuously reading transducer mounted in the gas plenum of the fuel pin.

Below fuel burnups of approximately 20,000 MWd/Te fuel expansion was governed by sintering, creep, and plastic flow. After the initial period of sintering *in situ* the fuel exhibited reasonably uniform expansion behavior. At approximately 20,000 MWd/Te the fuel-to-cladding diametral gap was found to have closed. This was evidenced by a decrease in the relative axial expansion of fuel at linear powers below approximately 13 kW/ft. The observed decrease in relative expansion is postulated to be due to mechanical fuel-cladding interactions. Above 13 kW/ft the fuel length change was erratic.

Fuel expansion as a function of burnup at constant power was nonuniform. For example, length increases followed by varying degrees of contraction were noted after a reactor shutdown and subsequent rise to power. The magnitudes of the expansions measured were at no time greater than would be predicted from the fuel center temperature and out-of-pile isothermal expansion data.

Data obtained can be used as input to the basis for establishing fuel column length changes in LMFBF cores.

Post-irradiation examination of the capsule showed the transducer calibration to have been unchanged by the neutron exposure.

2. INTRODUCTION

Knowledge of the physical properties of the mixed oxides of plutonium and uranium is necessary to determine the conditions under which breeder reactor cores may perform satisfactorily. The axial expansion of mixed-oxide fuel columns in-pile is a complex function of reactor history, fuel pin power level, and burnup*. The assured prediction of fuel behavior, or at least its upper and lower limits, is essential to the design of reactor cores that can operate satisfactorily.

The experimental study reported here involved an integral test conducted in-pile to determine the expansion of a 10-inch column of $(\text{Pu}_{0.25}, \text{U}_{0.75})\text{O}_{1.98}$ fuel under steady-state operating conditions and at various burnups during power traverses. The irradiation was conducted at linear powers sufficient to permit the effects of restructuring, sintering, and plastic flow on fuel length to be observed.

2.1 PRIOR WORK

2.1.1 Out-Of-Pile Experiments

General Electric

In an out-of-pile experiment performed by Asamoto, et al.,¹ a radial heat flow technique was utilized to provide a radial temperature gradient across a column of annular UO_2 pellets. Heating was provided by a tungsten resistance heater running through the center of the pellet stack. In these experiments the axial expansion of the flat end pellets was observed to be closely related to the pellet central temperature up to approximately 800°C**. At higher temperatures, the axial expansion was observed to be less than would be anticipated from the central temperature using isothermal data. This lower expansion was attributed to fuel column shrinkage caused by sintering and/or plastic flow.

*Predicting fuel column length changes due to reactor exposure can be done through application of basic materials data, but the results contain large uncertainties and can be altered by completely unknown effects of mechanical fuel cladding interactions. The main objective of this integral experiment was to bypass these uncertainties and measure length changes directly.

** Based on $\text{UO}_{2.0}$ thermal expansion measurements by Conway.²

In Asamoto's ¹ experiment, the axial expansion of the fuel column was reproducible after the first thermal cycle to 2200°C. At temperatures above fuel melting, the expansion was significantly less than that prior to melting.

In reference to in-pile conditions, Asamoto ¹ concluded that the in-pile parabolic temperature profile results in a larger portion of the fuel being at the higher temperatures where plastic flow can occur. Correspondingly, the surface temperature of the fuel in-pile is at a lower temperature; this results in a larger ΔT across the fuel in-pile, particularly at the higher temperatures. The in-pile temperature profile should cause the axial expansion of the fuel to be affected to a greater extent by plastic flow and/or sintering. The larger ΔT across the fuel in-pile should also create larger stresses, and lead to more severe cracking of the fuel. This in turn greatly affects the expansion characteristics of the fuel.

Oak Ridge National Laboratory

Martin and Weir ³ utilized a radiographic technique to measure the axial expansion of centrally heated, high density, hollow UO₂ pellets encapsulated in a type 304 stainless steel tube. These tests showed the thermal expansion of the pellet column to be very nearly a function of the central UO₂ temperature up to 2700°F for the case where the pellets are free standing within the fuel cladding. The Oak Ridge experiments, however, operated with a radial thermal gradient of 50° to 400°C/cm. These gradients were significantly lower than those used by Asamoto (900°C/cm) and may explain the difference in observed results.

Thermal cycling the capsules showed no detectable change in expansion characteristics of either the cladding or fuel. This was found to be true even when the pellets had fractured radially and made contact with the cladding.

2.1.2 In-Pile Experiments

AECL – Chalk River

Bain, et al., ⁴ irradiated cold-pressed and sintered UO_{2,00} pellets clad in various types of collapsed metal sheaths. These experiments indicated that the axial strain of the sheath depended on at least four variables:

- a. Original axial clearance
- b. Original diametral clearance
- c. Heat rating
- d. Strength of sheath

Notley ⁵ in similar experiments found that fuel pellets move relative to the sheath only until frictional forces are sufficient for the sheath to grip the fuel. A similar situation was observed in the E5F experiment at ~20,000 MWd/Te where little or no relative expansion was observed between the fuel and cladding while power traverses were being performed at heat ratings below about 13 kW/ft.

In a separate experiment, Notley and Harvey ⁶ measured the axial expansion of two UO₂ fuel elements clad in a collapsed Zircaloy sheath. In these experiments the fuel was observed to expand as the reactor power was increased, then to contract slowly during periods at constant power. Several days were required for the fuel to reach a constant length. Notley and Harvey ⁵ explained this behavior on the basis of a plastic core model. In this model the UO₂ pellets were considered to have a plastic core surrounded by a nonplastic, cracked annulus. The limit of the plastic core, defined as the temperature at which there is significant flow of the UO₂, was a function of the stress and time of stress application. Support for the plastic core model was provided by the fact that the change in fuel length corresponded to a temperature much lower than the fuel center temperature. In one instance, after a reactor shutdown, when the reactor power was finally raised to 42 MW the expansion was found to be greater than it was at that power prior to shutdown.

Notley and Harvey ⁶ concluded that the expansion of the element containing flat-ended pellets of UO₂ was governed by the expansion of the innermost nonplastic ring of UO₂ in the pellets. The temperature of this point was defined to be 750°C under normal conditions. Under conditions of high stress this temperature was considered to drop to as low as 400°C.

General Electric

Sparlaris ⁷ irradiated UO₂ pellets clad in type 304 stainless steel and Zircalov-2 utilizing mechanical markers to measure UO₂ movement during irradiation. Peak fuel temperatures reached 4700°F. No expansion or relative movement of the fuel into the plenum area of the fuel elements was observed during post-irradiation examination. Possible explanations for this result were fuel densification, fuel settling due to fracture, or longitudinal elastic strain of

the cladding. Spalaris ⁷ concluded that sheath restraint, densification of UO_2 , and, to a certain degree, plasticity of UO_2 at high temperature regions play important roles in influencing the cladding-fuel column relative movement in the axial direction.

Westinghouse

Baily ⁸ irradiated UO_2 in pins which had diametral gaps of 2 and 25 mils. Two things significant to the E5F experiment can be obtained from this data:

1. The fuel in the pin with 25-mil gap expanded as an unrestrained fuel column. The behavior of the experiment (E5F) described in this report at low burnup and power was expected to be similar.
2. The 2-mil gap resulted in interference between the cladding and fuel which resulted in only a small change in length of the fuel as the temperature increased. The E5F fuel was expected to behave similarly after sufficient burnup had been accumulated to relocate the fuel into the gap and cause appreciable fuel/cladding interaction. As will be discussed in a later section, both of these anticipated behaviors were observed.

3. EQUIPMENT AND FACILITIES

3.1 CAPSULE

The capsule design is shown in Figure A-1 of Appendix A. The capsule consisted of an outer stainless steel cylinder, one aluminum and one stainless steel thermal dam, the fuel pin, expansion bellows, and thermocouples. Volume for expansion of the NaK was provided by the bellows.

3.1.1 Capsule Instrumentation

The capsule was instrumented with 16 stainless-steel sheathed, chromel alumel, grounded-junction thermocouples. Six of the thermocouples were positioned for water calorimetry. The remaining 10 thermocouples were internal to the capsule. One thermocouple was positioned at the axial centerline of the transducer between the fuel pin and the outer containment. Nine were located in the annulus between the aluminum thermal dam and the fuel pin. These thermocouples were used to determine the linear power of the fuel pin. All thermocouples were connected to a standard 20-point 12-inch strip chart recorder. This recorder operated continuously during the test, ordinarily at a speed of 1 inch per day, but at 8 inches per hour during power traversing.

3.2 FUEL PIN

Details of the fuel pin are shown in Figure A-2 of Appendix A. The fuel pin consisted of the fuel column, plenum volume, and the linear displacement transducer.

The fuel column consisted of a 10-inch column of free-standing mixed-oxide pellets with 4 inches of UO_2 insulating pellets above the fuel and 1 inch below the fuel. Fuel and blanket parameters are shown in Table A-1 of Appendix A. The as-fabricated fuel-to-cladding diametral gap was 5.0 to 7.0 mils.

The fuel pin was helium filled and a gas plenum was designed around the transducer at the top of the fuel pin to accommodate the fission-product gases. The transducer was positioned within the gas plenum of the fuel pin above the fuel column. The transducer was coupled to the fuel by means of a transducer rod, welded to the plenum tube which rested on top of the blanket. The use of tubing only slightly smaller than the cladding tended to equalize the cladding and plenum tube temperatures, and hence to reduce the error involved in the correction factors. The tube also served to prevent fuel or blanket pellets from entering the plenum space near the transducer in the event that the capsule was inadvertently inverted after assembly.

3.2.1 Fuel Pin Instrumentation

The linear motion transducer was connected to another strip chart recorder through suitable balancing and zero-shift circuits. This strip chart recorder also operated continuously, at low speed except when power traversing was underway. The schematic circuit diagram is shown as Figure B-1 of Appendix B.

3.3 REACTOR

The irradiation was performed in the General Electric Test Reactor (GETR) utilizing a Mark IV-A V-Raft facility.⁹

4. PROCEDURE

4.1 EXPERIMENTAL

The V-Raft assembly within GETR kept the capsule centered in the peak flux throughout the irradiation and facilitated power cycling.

Through the use of this facility the axial expansion of the fuel was studied as a function of power and burnup.

4.1.1 Power Traversing

To obtain fuel response as a function of power at various burnups, the capsule was moved in and out of the neutron flux for periods of up to 8 hours. The capsule was moved by means of the V-Raft facility mentioned earlier. This procedure is hereafter referred to as power traversing. Power traverses were performed at 13 burnup levels during the irradiation period.

4.1.2 Fuel Movement as a Function of Burnup

During periods intermediate to power traversing the capsule operated at a steady-state power of 10.0 ± 0.5 kW/ft. The results are plotted as a function of burnup and are discussed in a later section.

The reactor was brought up to power on a ramp function extending over the first 24 hours. The position of the capsule was thereafter adjusted to maintain a power level in the pin of 10 ± 0.5 kW/ft with the following exceptions:

1. The 13 occasions when the capsule was cycled in and out of the reactor.
2. During the 38 reactor shutdowns.
3. For a week just prior to the last traverse, at 43,700 MWd/Te, the fuel element was operated at about 6 kW/ft.

The reactor power was maintained constant at 50 MW throughout the whole experiment except for the shutdowns noted. The position of the capsule was adjusted for power traversing and to obtain the 6 kW/ft for the week prior to the last power traverse.

On 13 occasions during the 274-day run the power level of the pin was traversed by moving the capsule, with the V-Raft assembly, in and out of the neutron flux. The purpose of this power traversing was to determine the effect of power level on the expansion of the fuel. Each traverse was accomplished in steps (usually 30 to 40) over an interval of some 6-8 hours. During these traverses the strip-chart recorders were run at high speed, approximately 8 inches per hour. The occasions for power traversing were thoughtfully chosen to study in some detail the fuel behavior at (1) very low burnup, (2) the burnup where the fuel had reduced the initial 5.5-mil (diametral) gap to near zero, and (3) high burnup. The burnups and times when power traverses were made are:

Burnup MWd/Te	Days After Start
400	2
600	3
800	4
1,000	5
19,200	108
19,400	109
24,100	143
24,200	144
33,400	201
37,800	226
38,100	228
41,700	253
43,700	271

The test was terminated after 44,000 MWd/Te when a lead wire to the linear motion transducer broke, and further length measurements could not be made.

The complete (condensed) time history of the reactor power and pin power during the entire 274-day run is shown in Figure 4-1, excluding power traverses.

The thermocouple temperatures and the indicated length changes were recorded continuously on strip chart recorders.

After the test was completed, an extensive post-irradiation examination of the capsule and its contents was made.

4.2 CALIBRATION

4.2.1

The chromel-alumel thermocouples used were standard units and the calibrations provided by the manufacturer were used.

4.2.2

The calibration of the linear motion transducer with its associated circuitry including the strip-chart recorder was accomplished as follows.

Prior to encapsulation the measuring transducer and a duplicate were placed in a special fixture fitted with a vernier micrometer for adjusting the transducer probe. Paired readings of the strip chart and the micrometer established the calibration curve. During the experiment the measuring transducer was inaccessible. Prior to each traverse the duplicate transducer was placed in the transducer circuitry with the special fixture and readings compared with the initial calibration. The recorder was then adjusted to duplicate the calibration curve obtained at the beginning of the experiment. After irradiation the transducer was again calibrated. This calibration and the calibrations of the duplicate, dummy, transducer were essentially identical.

Figure 4-1. Reactor Power-Fuel Pin Power During E5F Irradiation

4.3 ANALYTICAL

4.3.1 Power

The temperatures of the thermocouples (together with information regarding their location) were input to a computer code. This code computed the linear power of the fuel pin as well as the temperature at the center of the fuel, at its surface, and the volume-average temperature.

Since pin power is directly related to thermocouple temperature this computation amounted to a recalibration of the temperature strip chart into a chart of pin power as a function of time.

4.3.3 Change in Length

To obtain absolute values of fuel expansion, additive corrections are required because the transducer responds to the net sum of the changes in length of all the components. This involves several components in addition to the fuel itself.

These correction factors were calculated based on length, temperature coefficient of expansion, and directional effect of temperature changes of fuel pin parts on the transducer response. Structural members of the fuel pin were divided into three regions along the fuel pin length as shown in Figure 4-2.

Regions I, II, and III were the fuel, plenum, and transducer regions of the fuel pin, respectively. By analyzing the structural design of the fuel pin, the directional effect of length changes of pertinent members on transducer response was determined. By calculating the average temperature of each member as a function of power, the magnitude of each change could be determined.

Table 4-1 lists each fuel pin member along with the direction of effect on transducer output produced by a power increase. Magnitudes of length correction factors are plotted against power in Appendix B for each member concerned. Figures B-2, B-3, and B-4 show the correction factor for individual components. Figure B-5 shows the overall factor summing the individual factors with the appropriate signs as indicated in Table 4-1.

Table 4-1
DIRECTIONAL RESPONSE AND EFFECT ON
TRANSDUCER READINGS OF FUEL PIN MEMBERS

		Direction of Power Change	Change in Member Length	Effect on Transducer Output	Sign of Correction to Transducer Output
Region I	Cladding	Positive	Positive	-	+
Region II	Cladding	Positive	Positive	-	+
	Plenum Tube	Positive	Positive	+	-
Region III	Cladding	Positive	Positive	-	+
	Transducer Rod	Positive	Positive	+	-
	Transducer Body	Positive	Positive	+	-

Figure 4-2. Schematic Illustration of E5F Fuel Pin

An example of the application of these factors, for power step No. 4, in Figure 5-1 (at 28 minutes), is given below.

This power step increased the power to 9.99 kW/ft as determined from the thermocouple temperatures. The measured relative axial expansion after this step (from the upper curve of Figure 5-1) ranged from 0.068 to 0.0505 and the last value is considered to be the most significant. From the curves in Appendix B the additive correction factors for the other components, for a pin power of 9.99 kW/ft, are found to be:

Region	Member	Factor
I	Cladding	+0.0880
II	Cladding	+0.0105
	Plenum Tube	-0.0121
III	Cladding	+0.0066
	Transducer Rod	-0.0134
	Transducer Body	-0.0127
Net Correction *		+0.0668

*This net correction factor could have been obtained directly from Figure B-5.

Transducer Output	0.0505
Correction	<u>0.0668</u>
Net Fuel Length Increase	0.1173

This is an elongation of 1.17% over the 10-inch fuel length and is the value plotted for step 4 on Figure 5-2. The fuel center temperature for that step (1420°C) comes from Figure C-1 of Appendix C.

5. RESULTS AND DISCUSSION

5.1 POWER TRAVERSING

The results of power traversing are reported by two different methods. In the first case, the axial expansion of the fuel relative to cladding is plotted versus time (see upper curve of Figure 5-1 for example) in conjunction with the corresponding power curve. These plots are time continuous and as such show every movement of the fuel relative to the cladding during the traverse. They amount to the chart records of the transducer output after calibration but without correction factors. In the second case, the percent axial elongation is plotted against the fuel center temperature. The percents of elongation in these curves indicate expansion of the fuel itself, not merely its change relative to the cladding. Adjustments in the transducer readings were made as described in subsection 4.3. The percent elongation curves are marked with arrows and symbols to give an indication of the time and magnitude of power change during the power traverse which each point represents. In determining each point on the percent elongation curve, the final value of relative axial expansion for that specific power step was used. The following is a discussion of the results of individual power traverses.

5.1.1 400 MWd/Te

The first power traverse, shown in Figure 5-1, was performed during the second day of operation after 400 MWd/Te burnup. The relative expansion curve shows three phenomena which had been anticipated qualitatively, but not quantitatively.

The first phenomenon, which diminishes with increasing time and power, is a transient expansion. At the initial point of power increase the fuel undergoes a large expansion followed by a contraction which is at first rapid but then decreases in rate. This implies that there are two processes taking place simultaneously. The first is the prompt expansion of the fuel when the power is increased. The second process is the plastic flow of the fuel when at least some of it has exceeded the softening temperature. This plastic flow is consistent with the mechanism proposed by Notley and Harvy. ⁶ As time progresses the fuel continues to flow plastically until the available void space within the fuel has

Figure 5-1. Power Traverse Performed After 400 MWd/Te, showing the relative fuel-cladding expansion as a function of fuel pin power

been utilized and plastic flow diminishes or until pellet interfaces meet at a nonplastic outer annulus and plastic flow again diminishes. Subsequent power increases cause more fuel to operate in the plastic inner region of the fuel. Power increases cause an initial bowing effect of end faces causing the hottest portion of the plastic fuel to again make contact at a minute point and cause an initial increase in length followed by a decrease. However, because plastic fuel is now hotter than during the previous power change, plastic flow occurs at a faster rate thus causing less of an expansion each time the power is raised.

The second phenomenon, which is repeatedly apparent in this experiment and was reported also by Notley and Harvey,⁶ is that of fuel contraction while running at constant power. The reason for this reduction in length was explained as being caused by pellet sintering and/or plastic flow, both of which may cause densification and subsequent fuel column shortening. Credence may be given to this explanation by noting the observed difference in dimensional behavior upon cooling, shown in the temperature plot (Figure 5-2), which indicates that densification has occurred in agreement with the out-of-pile work performed by Asamoto, et al.¹ Also the expansion corresponds to a temperature much less than the fuel center temperature.

The third phenomenon, which occurred occasionally, is the sudden increase in fuel length during cooling. This is observed in both the relative expansion and absolute elongation curves. This might be explained by pellet cracking as a result of stresses imposed by differential contraction between pellet surface and center. The fuel center is now more dense than the outer portion of the fuel and, as a result, differs in thermal expansion characteristics.

Furthermore, due to the temperature characteristics of the capsule environment, the capsule outer temperature remains essentially constant throughout each power traverse, which implies that for a given power change, the fuel surface will undergo a smaller change in temperature than will the fuel center. As a result, stresses occur causing circumferential cracking of the fuel pellets and a sudden expansion occurs.

Figure 5-2. Absolute Fuel Elongation Versus Fuel Center Temperature

5.1.2 600, 800, and 1000 MWd/Te

The next three traverses (see Figures 5-3 to 5-8) were performed on the 3 days immediately subsequent to the first traverse, after 600, 800, and 1000 MWd/Te burnup. Evidence of all three phenomena previously mentioned still existed, however in diminished magnitude for all three cases. The amount of fuel movement observed is becoming more reproducible during the course of each traverse.

Figure 5-3. Power Traverse Performed After 600 MWd/Te, showing the relative fuel-cladding expansion as a function of fuel pin power

Figure 5-4. Absolute Fuel Elongation Versus Fuel Center Temperature

Figure 5-5. Power Traverse Performed After 800 MWd/Te, showing the relative fuel-cladding expansion as a function of fuel pin power

Figure 5-6. Absolute Fuel Elongation Versus Fuel Center Temperature

Figure 5-7. Power Traverse Performed After 1000 MWd/Te, showing the relative fuel-cladding expansion as a function of fuel pin power

Figure 5-8. Absolute Fuel Elongation Versus Fuel Center Temperature

5.1.3 19,200 and 19,400 MWd/Te

Power traverses performed at 19,200 and 19,400 MWd/Te (Figures 5-9 to 5-12) burnup showed no relative axial expansion of the fuel when the power was lowered and then raised to about 13 kW/ft. This lack of response is attributed to fuel-cladding interactions and agrees well with results reported by Baily⁸ for the case of a 2-mil diametral gap. Above 13 kW/ft the fuel behaved quite erratically. This behavior may be explained by the sudden release of fission gases having a piston effect on the fuel column and insulator pellets. At lower powers fuel temperatures are too low to allow the release of appreciable amounts of fission gases. At 13 kW/ft 10% of the fuel volume is calculated to be operating at temperatures high enough to permit release of 100% of the fission gases which were accumulated at lower powers in this volume. This calculation is in agreement with results reported by Nelson.¹⁰

Figure 5-9. Power Traverse Performed After 19,200 MWd/Te, showing the relative fuel-cladding expansion as a function of fuel pin power

Figure 5-10. Absolute Fuel Elongation Versus Fuel Center Temperature

Figure 5-11. Power Traverse Performed After 19,400 MWd/Te, showing the relative fuel-cladding expansion as a function of fuel pin power

Figure 5-12. Absolute Fuel Elongation Versus Fuel Center Temperature

5.1.4 24,100 and 24,200 MWd/Te

The power traverses performed at 24,100 and 24,200 MWd/Te burnup are shown in Figures 5-13 and 5-14. Fuel response to power changes during these traverses is similar to that observed at ~19,000 MWd/Te where the expansion behavior was erratic and unpredictable. One possible explanation for this behavior is that the pellets expand and lock into the cladding and thus create axial gaps in the fuel. The pellets subsequently free themselves, close the axial gaps, and significant contraction of the fuel column occurs. In general, the expansion behavior of the fuel column became more erratic and unpredictable with increasing burnup.

Figure 5-13. Power Traverse Performed After 24,100 MWd/Te, showing the relative fuel-cladding expansion as a function of fuel pin power

Figure 5-14. Power Traverse Performed After 24,200 MWd/Te, showing the relative fuel-cladding expansion as a function of fuel pin power

5.1.5 33,400 MWd/Te

The next power traverse, performed after 33,400 MWd/Te (see Figures 5-15 and 5-16), shows close correspondence of the fuel length to the power changes as compared to the response observed at 24,100 and 24,200 MWd/Te burnup. This difference is believed to be due to the differences in the physical condition of the fuel at the times of the traverses. The earlier traverses were performed after the fuel had operated for a relatively long period of time at a power of 10.0 ± 0.5 kW/ft which allowed the fuel to sinter, relocate, and bind against the cladding. The power traverse after 33,400 MWd/Te was initiated while the reactor was coming up to full power after a reactor scram. As a result of the thermal shock caused by the scram procedure, the fuel is postulated to have been extensively broken up and free to move with relatively slight fuel-cladding interaction. No erratic behavior was observed during this traverse. This might be explained in two manners: during this traverse the power was never raised high enough to generate temperatures which would allow the release of appreciable amounts of fission gases or, since this traverse was performed after a reactor down period, fission gases might have previously escaped as a result of fuel cracking caused by the shutdown procedure.

5.1.6 37,800 and 38,100 MWd/Te

Figure 5-17 shows the fuel response during the power traverse performed at a fuel burnup of 37,800 MWd/Te. In general, the fuel response is quite erratic but does tend to follow the corresponding power changes. With an increase in power there is a general increase in fuel column length with one exception. Early in the power traverse a significant contraction of the fuel column was observed. This is attributed to the closing of an axial gap in either the fuel or insulator pellet column.

At 38,100 MWd/Te (Figure 5-18) the fuel response remained quite erratic. Midway through the power traverse an attempt was made to thermally shock the fuel by rapidly decreasing the power. The transducer response indicated a rapid increase in pellet column length which could be attributed to breaking up of the fuel resulting in a longer fuel column length. Subsequent increases in power nevertheless resulted in erratic fuel column length behavior. The magnitude of such erratic fluctuations, however, was significantly less than that observed before thermal shocking and the observed length fluctuations are consistent with the hypothesis of either sudden pellet cracking or fission gas bursts.

5.1.7 41,700 and 43,700 MWd/Te

The power traverse performed at 41,700 MWd/Te burnup (Figure 5-19) was very similar in appearance to that at 37,800 MWd/Te (Figure 5-17). Similarly, midway through the traverse an attempt was made to thermally shock the fuel by rapidly decreasing the operating power. As before, the fuel appeared to expand followed by erratic fluctuations of lesser magnitude than those before the thermal shock.

The power traverse performed at 43,700 MWd/Te is shown in Figure 5-20. Prior to running this power traverse the fuel element was allowed to operate at about 6 kW/ft for a period of 1 week (4 kW/ft lower than the operating power prior to the previous power traverses). The expansion resulting from this power traverse is erratic with the expansion being less than during previous intermediate power traverses with the exception of the traverse at 33,400 MWd/Te. While no explicit explanation for this behavior is available it is consistent with the suggestion that the response during a given power traverse is dependent upon previous operating conditions as also indicated in subsection 5.1.5.

5.2 AXIAL EXPANSION AS A FUNCTION OF BURNUP

Shown in Figure 5-21a are the fuel relative expansion results as a function of time for the entire 274 days with fuel burnup superimposed. These results indicate that the fuel element length behavior is erratic and unpredictable on the basis of burnup alone. The fuel length behavior appears to be a function of reactor power, shutdown procedure, and length of time since last shutdown. For comparison purposes the fuel pin and reactor power are shown in Figure 5-21b. Invariably, the fuel element length increase after a reactor shutdown and subsequent rise to power was greater than that observed prior to the shutdown. After some time at power the fuel column invariably contracted to a length near to what it had been prior to the shutdown. This behavior is attributed to fuel cracking caused by thermal shocking of the fuel and subsequent sintering and crack healing.

Figure 5-15. Power Traverse Performed After 33,400 MWd/Te, showing the relative fuel-cladding expansion as a function of fuel pin power

Figure 5-16. Absolute Fuel Elongation Versus Fuel Center Temperature

Figure 5-17. Power Traverse Performed After 37,800 MWd/Te, showing the relative fuel-cladding expansion as a function of fuel pin power

Figure 5-18. Power Traverse Performed After 38,100 MWd/Te, showing the relative fuel-cladding expansion as a function of fuel pin power

Figure 5-19. Power Traverse Performed After 41,700 MWd/Te, showing the relative fuel-cladding expansion as a function of fuel pin power

Figure 5-20. Power Traverse Performed After 43,700 MWd/Te, showing the relative fuel-cladding expansion as a function of fuel pin power

Figure 5-21b. Reactor Power-Fuel Pin Power During E5F Irradiation

6. SUMMARY OF RESULTS, AND CONCLUSIONS

In summary, the results of this experiment are:

1. A successful means was developed for continuously measuring the change in axial length of an operating mixed-oxide fuel column.
2. Below 20,000 MWd/Te, axial expansion as a function of power level was reproducible.
3. Above 20,000 MWd/Te, the axial expansion was erratic and unpredictable.
4. The expansion was always less than the value computed from fuel center temperature and out-of-pile isothermal expansion data.

Conclusions, based largely on prior work and supported by this experiment, are:

1. Early in life such things as pellet sintering, plastic flow, and pellet cracking affect fuel column length significantly.
2. Closure of the initial 5.0-mil (diametral) fuel-cladding gap occurred at less than 20,000 MWd/Te at a power level of 10 kW/ft.
3. Closure of the fuel-cladding gap can result in fuel-cladding interaction which can prevent or hinder relative movement between the fuel and cladding.
4. At high burnups the axial dimensions of a column of mixed-oxide fuel pellets behave anomalously. Pellet cracking and fission-gas release appear to affect dimensional behavior.
5. Dimensional behavior during a power excursion is affected by prior operating power and reactor shutdown history.
6. A prediction of fuel expansion based on fuel center temperature and out-of-pile isothermal expansion data will always be larger than the actual value.

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APPENDIX A

Fuel Parameters

Capsule Drawings

Fuel Pin Drawings

Table A-1
FUEL, BLANKET AND INSULATOR FABRICATION PARAMETERS

Fuel — Mixed Oxide

% Pu/Pu+U	25.32
% U-235/U	11.26
O/M	1.976
Type	Sintered Pellet
Powder Preparation	Co-Precipitated
Density, %TD	92.2
Fuel Column Height, inches	10.0
Diametral Gap, mils	5.0—7.0
Pellet Diameter	0.2130—0.2150

Insulator and Blanket — UO_2

% U-235/U	Natural
O/M	1.998
Type	Sintered Pellet
Powder Preparation	Co-Precipitated
Density, %TD	95.8
Insulator Length, inches	1.0
Blanket Length, inches	4.0

Figure A-2. E5F Fuel Pin Design

VIEW SHOWING PROTECTIVE TUBE THAT IS TO BE USED DURING HANDLING & SHIPMENT

AFTER ASSEM. GRA-ETCH MARK
ON END PLUG AS SHOWN 180°
FROM BOTTOM EL. TACK WELD
OF WIRE PIE

AS BUILT

9. Hacks or scratches per cm^2 .005 inches or 10% of cm^2 thickness shall not be allowed.
 10. After spiral wrapping per spec. 332 - .006 I.D. by 5" long.
 11. Weld number in diamond $\square$ indicate weld identification only.
 12. Radiograph test per orientation full length is duplicate. This radiograph to be made in vertical position with boluses up.
 13. Post pellets to be laid through and opposite the transducer. P15 spiral wire shall be clamped at front and end and plug seal up to middle and top tested. P16 will then be welded to the end of the first weldment of P15 middle and top tested.
 14. All welds to be leak checked with Helium mass spec. A leak greater than 3×10^{-8} cc/sec. H.T.P. shall not be acceptable.
 15. All radiographs to be reviewed by responsible engineer.
 16. All weld penetrations to be reviewed by responsible engineer.
 17. All fusion welds shall have at least 90% depth of penetration.
 18. All thickness shall start to be clamped per spec. 670C-670D and penetrated per spec. 670A-771. Weld groove shall have seal to be completed following welding and penetration.
- NOTE:

NOTES

UNLESS OTHERWISE SPECIFIED USE THE FOLLOWING:			GENERAL ELECTRIC		91D754
PARTS IDENTIFICATION	QUANTITY	REMARKS	QTY	UNIT	DESCRIPTION
145A5481	125				FUEL PIN
					PART MADE FOR PCR E-5-F
					NEXT ASSY 106644961
1	1				END PLUG 211A7134FI
1	2				END CAP 211A7135FI
1	3				SPACER 211A7136FI
1	4				SPACER 211A7137FI
1	5				END CAP 211A7138FI
1	6				END CAP 211A7139FI
AR 7	1				REELY BUSHET 211A7144P2
AR 8	1				REELY 211A7144P1
1	9				TUBE 211A7145FI
1	10				WIRE 10555085841
1	11				TUBE 211A7146FI
2	12				TUBE 117C7912FI
1	13				TUBE 100A435WALL 10.6-306 070001 (NOT)
1	14				BELLOWS ROBERTSON-FULTON ACO754-AB7
1	15				WIRE DSB DIA 1/8IN DIA 800-200 WIRE STPL
1	16				TRANS PUCER PHYSICAL DESIGN CROFT MODEL 100-1
1	17				WIRE CDS 2 A 3.5 WIRE MAGNETIC MOUNTED
1	18				CABLE 48 WIRE OR 547 070001 NORTH
1	19				ARMATURE 0066-544-7 (HIL) 0.
1	20				WIRE 10555085841
1	21				TUBE 211A7146FI

IS TO BE USED TO PROTECT LEADOUTS
DURING HANDLING & SHIPMENT

GEAP-10403

DESCRIPTION OF GROUP	REVENUE	POINTS TO
4 A-WARE B-WARE C-WARE D-WARE E-WARE F-WARE G-WARE H-WARE I-WARE J-WARE K-WARE L-WARE M-WARE N-WARE O-WARE P-WARE Q-WARE R-WARE S-WARE T-WARE U-WARE V-WARE W-WARE X-WARE Y-WARE Z-WARE	1 A-ADDED 2 A-ADDED 3 A-ADDED 4 A-ADDED 5 A-ADDED 6 A-ADDED 7 A-ADDED 8 A-ADDED 9 A-ADDED 10 A-ADDED 11 A-ADDED 12 A-ADDED 13 A-ADDED 14 A-ADDED 15 A-ADDED 16 A-ADDED 17 A-ADDED 18 A-ADDED 19 A-ADDED 20 A-ADDED 21 A-ADDED 22 A-ADDED 23 A-ADDED 24 A-ADDED 25 A-ADDED 26 A-ADDED 27 A-ADDED 28 A-ADDED 29 A-ADDED 30 A-ADDED 31 A-ADDED 32 A-ADDED 33 A-ADDED 34 A-ADDED 35 A-ADDED 36 A-ADDED 37 A-ADDED 38 A-ADDED 39 A-ADDED 40 A-ADDED 41 A-ADDED 42 A-ADDED 43 A-ADDED 44 A-ADDED 45 A-ADDED 46 A-ADDED 47 A-ADDED 48 A-ADDED 49 A-ADDED 50 A-ADDED 51 A-ADDED 52 A-ADDED 53 A-ADDED 54 A-ADDED 55 A-ADDED 56 A-ADDED 57 A-ADDED 58 A-ADDED 59 A-ADDED 60 A-ADDED 61 A-ADDED 62 A-ADDED 63 A-ADDED 64 A-ADDED 65 A-ADDED 66 A-ADDED 67 A-ADDED 68 A-ADDED 69 A-ADDED 70 A-ADDED 71 A-ADDED 72 A-ADDED 73 A-ADDED 74 A-ADDED 75 A-ADDED 76 A-ADDED 77 A-ADDED 78 A-ADDED 79 A-ADDED 80 A-ADDED 81 A-ADDED 82 A-ADDED 83 A-ADDED 84 A-ADDED 85 A-ADDED 86 A-ADDED 87 A-ADDED 88 A-ADDED 89 A-ADDED 90 A-ADDED 91 A-ADDED 92 A-ADDED 93 A-ADDED 94 A-ADDED 95 A-ADDED 96 A-ADDED 97 A-ADDED 98 A-ADDED 99 A-ADDED 100 A-ADDED	DL
950000 573.67 C-WARE D-WARE E-WARE F-WARE G-WARE H-WARE I-WARE J-WARE K-WARE L-WARE M-WARE N-WARE O-WARE P-WARE Q-WARE R-WARE S-WARE T-WARE U-WARE V-WARE W-WARE X-WARE Y-WARE Z-WARE	100 A-ADDED 101 A-ADDED 102 A-ADDED 103 A-ADDED 104 A-ADDED 105 A-ADDED 106 A-ADDED 107 A-ADDED 108 A-ADDED 109 A-ADDED 110 A-ADDED 111 A-ADDED 112 A-ADDED 113 A-ADDED 114 A-ADDED 115 A-ADDED 116 A-ADDED 117 A-ADDED 118 A-ADDED 119 A-ADDED 120 A-ADDED 121 A-ADDED 122 A-ADDED 123 A-ADDED 124 A-ADDED 125 A-ADDED 126 A-ADDED 127 A-ADDED 128 A-ADDED 129 A-ADDED 130 A-ADDED 131 A-ADDED 132 A-ADDED 133 A-ADDED 134 A-ADDED 135 A-ADDED 136 A-ADDED 137 A-ADDED 138 A-ADDED 139 A-ADDED 140 A-ADDED 141 A-ADDED 142 A-ADDED 143 A-ADDED 144 A-ADDED 145 A-ADDED 146 A-ADDED 147 A-ADDED 148 A-ADDED 149 A-ADDED 150 A-ADDED 151 A-ADDED 152 A-ADDED 153 A-ADDED 154 A-ADDED 155 A-ADDED 156 A-ADDED 157 A-ADDED 158 A-ADDED 159 A-ADDED 160 A-ADDED 161 A-ADDED 162 A-ADDED 163 A-ADDED 164 A-ADDED 165 A-ADDED 166 A-ADDED 167 A-ADDED 168 A-ADDED 169 A-ADDED 170 A-ADDED 171 A-ADDED 172 A-ADDED 173 A-ADDED 174 A-ADDED 175 A-ADDED 176 A-ADDED 177 A-ADDED 178 A-ADDED 179 A-ADDED 180 A-ADDED 181 A-ADDED 182 A-ADDED 183 A-ADDED 184 A-ADDED 185 A-ADDED 186 A-ADDED 187 A-ADDED 188 A-ADDED 189 A-ADDED 190 A-ADDED 191 A-ADDED 192 A-ADDED 193 A-ADDED 194 A-ADDED 195 A-ADDED 196 A-ADDED 197 A-ADDED 198 A-ADDED 199 A-ADDED 200 A-ADDED	DL

STAINLESS STEEL

ALUMINUM

1. OUTER CONTAINMENT
2. ALUMINUM THERMAL DAM
3. STAINLESS STEEL THERMAL DAM
4. FUEL CLADDING
5. NaK ANNULUS
6. THERMOCOUPLES
7. FUEL

Figure A-3. Schematic Illustration of E5F Capsule Cross Section

APPENDIX B

Transducer Circuitry and Correction Factors

Figure B-1. Schematic Illustration of Transducer Circuitry

Figure B-2. Transducer Correction Factor for Region 1

Figure B-3. Transducer Correction Factors for Region 2

Figure B-4. Transducer Correction Factors for Region 3

Figure B-5. Cumulative Correction Factors for Regions 1, 2, and 3

APPENDIX C

Fuel Temperatures

Figure C-1. Fuel Temperature Versus Power

APPENDIX D**POST-IRRADIATION EXAM**

Following irradiation, the capsule was destructively examined at the General Electric Radioactive Materials Laboratory (RML) at the Vallecitos Nuclear Center near Pleasanton, California.

Post-irradiation examination of the capsule consisted of:

1. Neutrography
2. Gamma scan of encapsulated fuel pin
3. Burnup and flux wire analysis
4. Fuel pin profilometry
5. Fission-gas analysis
6. Metallographic examination of the fuel pin
7. Transducer calibration

D.1 GAMMA SCAN

No unusual peaks or depressions were observed in the scan. The gamma activity profile over the fuel region was extremely flat with two exceptions. At each end of the fuel column high-activity peaks were observed. The peaks were formed as a result of end peaking and formation of fission products. The gamma activity over the plenum decreased uniformly to the position of the transducer where the activity was near that of the background.

D.2 BURNUP DETERMINATION AND FLUX WIRE RESULTS

Fuel burnup was determined by radiochemical analysis for Nd-148 and by mass spectrometer for heavy element burnup values. Results of the two analyses are given in Table D-1. Flux wire results for neutron fluence are given in Table D-2.

Aluminum-cobalt flux wires were used to determine the total mixed neutron fluence. Two samples of the flux wire were used for analysis. One sample of the wire was taken from the center of the fuel section and one from over the transducer probe in the gas plenum of the fuel pin just below the transducer (see fuel pin sectioning diagram). The flux wire results indicate that the transducer experienced less fluence than it had been rated for (1×10^{22} nvt total).

Table D-1
BURNUP AND FLUX WIRE RESULTS

A. Fission Product Burnup Values $\pm 3\%$ ^(a)

Isotope	Atom Percent Fissions	MWd/Te
Nd-148	5.4613	52407

B. Heavy Element Burnup Values

Isotope	Atom Percent Fissions	MWd/Te
U-235	0.9986	
Pu-239	3.9016	
Pu-241	0.0001	
U-238	0.0517	
Total	4.9520	48610

C. Aluminum-Cobalt Flux Wires

Position	nvt (n/cm^2)
Over Plenum	2.4×10^{20}
Over Fuel	8.2×10^{20}

(a) Rider, B.F., Ruiz, C.P., Peterson, Jr., J.P. and Smith, F.R.,
*Determination of Neodymium-148 in Irradiated Uranium and
Plutonium as a Measure of Burnup*, March 1967 (GEAP 5354).

Table D-2
FISSION GAS ANALYSIS

A. Percent Fission Gas Released

Kr-85 Produced, Atoms	9.7×10^{18}
Kr-85 Released, Atoms	6.3×10^{18}
% Kr-85 Released	65

B. Mass Spectrometric Analysis

Mass/Charge	Probable Species	Normalized Peak Heights (%)
2	H_2^+	1.3
4	He^+	7.9
14	N^{++}	0.01
15	CH_3^+	0.01
16	CH_4^+	0.02
28	$N_2^+, (CO^+)$	0.33
40	Ar^+	0.06
44	CO_2^+	0.07
83-86	Kr^+	6.59
131-136	Xe^+	83.69

C. Gas Chromatography

Species	Volume %
H_2	N.D.
He	26.2 ± 0.1
N_2	0.36 ± 0.05
CH_4	N.D.
Ar	0.03 ± 0.01
CO	N.D.
CO_2	0.04 ± 0.01
O_2	<0.01
Kr	4.92 ± 0.01
Xe	64.8 ± 0.1
TOTAL	96.4

D.3 FUEL PIN PROFILOMETRY

Pre- and post-irradiation profile measurements of the fueled section of the fuel pin are shown in Figures D-1 and D-2. No significant diametral cladding increases were measured over the fueled section of the fuel pin. A slight amount of ovality, however, did occur over the entire fueled length of the pin. Near the interface between the fuel and lower insulator pellets significant ovality occurred. A difference in diameter of about 2.5 mils around the circumference occurred at this point. The direct cause of the ovality at that particular point is unknown.

D.4 FISSION-GAS ANALYSIS

The percent fission gas released based on the measured Kr-85 content of the gas released from the fuel pin is listed in Table D-2. Results from gas chromatography and mass spectrometry are also listed.

D.5 METALLOGRAPHIC EXAMINATION

A photograph of the fuel pin prior to sectioning is shown in (a) of Figure D-3. The surface of the fuel pin was bright in appearance with the exception of one spot in the vicinity of the fuel-insulator interface near the bottom of the fuel pin. This spot corresponds very nearly to the position of extreme ovality observed in the profilometer traces (Figure D-2). Figure D-3 (b) and (c) show photographs of this portion of the pin and indicate a surface deposit and discoloration of the cladding. This surface deposit could explain the high side of the ovality observed in the profilometer traces but not the low side.

Figure D-4 shows a sectioning diagram of the fuel pin along with photomicrographs of the as-cut transverse sections of the fuel pin. The as-cut sections show a uniform central void over the length of the fuel pin indicating a flat axial flux profile in agreement with the gamma scan.

Two longitudinal metallography sections (Figures D-5 and D-6) were taken of the upper and lower fuel insulator interfaces. The sections indicate a slight interaction between the fuel and the contacting insulating pellet (UO_2) at each end of the fuel column with the greater interaction at the top of the fuel column.

One transverse cross section (Figure D-7) of the pin was taken near the center of the fuel column for metallographic examination (cross section 57011 in Figure D-4) of the fuel and cladding.

The photomicrograph shown in Figure D-7 shows the characteristic central void and columnar grains extending from the central void to the outer regions of the fuel. At several radial locations large metallic particles were observed at or near a crack.

Metallic stringers extending from the fuel to the cladding were observed wherever a radial fuel crack propagated to the cladding. Regions 1 and 4 in Figure D-7 note two examples of these metallic stringers.

Figure D-8 shows a high magnification photomicrograph of region 1 after cladding etch. No indication of cladding attack was observed in the vicinity of the metallic stringer. Figure D-9 shows 500X photomicrographs of region 4 of Figure D-7 in both the polished and etched conditions. Figure D-10 shows 500X photomicrographs of region 2 in which a slight matrix reaction occurred between the fuel and cladding.

Figure D-11 shows 500X photomicrographs of region 3 in which a uniform reaction has occurred between the fuel and cladding. This reaction zone appears as a gray bond extending along the cladding inside surface approximately 0.8 mils wide. Fuel etching attacked the reaction zone to a limited extent as shown in (b) of Figure D-11. Cladding etching completely dissolved the reaction zone as evidenced by comparing (a) with (c) in Figure D-11.

*Figure D-1. Pre-Irradiation Profilometer Measurements
Over Fueled Region of Pin*

*Figure D-2. Post-Irradiation Profilometer Measurements
Over Fueled Region of Pin*

(a) 54381-3

(b) 54384

(c) 54385

Figure D-3. Photograph of Fuel Pin Prior to Sectioning

Figure D-4. Fuel Pin Sectioning Diagram and Photomicrographs of As-cut Fuel Sections

Figure D-5. Fuel-Insulator Interface at Top of Fuel Column

Figure D-6. Fuel-Insulator Interface at Bottom of Fuel Column

A 350-13
~25X

*Figure D-7. Photomicrographs of As-polished Cross Section
Taken Near the Center of the Fuel Pin*

A 350-20
~ 500X

*Figure D-8. Region 1 of Figure D-7 in the cladding-etch condition
(5% Chromic Acid, Electrolytic Etch, 6V, 10 seconds)*

A 350-07
~500X

(a) AS POLISHED

A 350-16
~500X

(b) FUEL ETCH
10% HNO_3 - 20% H_2O_2 -
70% H_2O
35 MINUTES

A 350-23
~500X

(c) CLAD ETCH
5% CHROMIC ACID,
ELECTROLYTIC ETCH,
6 V, 10 SECONDS

Photos reduced to 85%
for reproduction

Figure D-9. Photomicrographs of Region 4 in Figure D-7

A 350-03
~500X

(a) AS POLISHED

A 350-18
~500X

(b) FUEL ETCH
10% HNO_3 - 20% H_2O_2 - 70% H_2O
35 MINUTES

A 350-25
~500X

(c) CLAD ETCH
5% CHROMIC ACID,
ELECTROLYTIC ETCH,
6V, 10 SECONDS

Photos reduced to 85%
for reproduction

Figure D-10. Photomicrographs of Region 2 in Figure D-7

A 350-04
~ 500X

(a) AS POLISHED

A 350-17
~ 500X

(b) FUEL ETCH
10% HNO_3 -20% H_2O_2 -
70% H_2O 35 MINUTES

A 350-24
~ 500X

(c) CLAD ETCH
5% CHROMIC ACID

Photos reduced to 85%
for reproduction

Figure D-11. Photomicrographs of Region 3 in Figure D-7

Small metallic particles thought to be fission products were seen to be well dispersed within the columnar grain growth region. Larger metallic particles were found to be situated near the termination point of columnar grain growth always within a fuel crack or void space. Metallic stringers were observed emanating from the fuel to the cladding wherever a crack in the fuel extended to the fuel-cladding interface. Several regions containing a reaction zone were found at the fuel-cladding interface. The attack was always uniform showing no preference for grain boundaries and always having a thickness of less than 1 mil.

D.6 TRANSDUCER CALIBRATION

After the fueled section of the fuel pin had been sectioned, the transducer was retrieved from the gas plenum of the fuel pin. The physical appearance of the transducer after irradiation was essentially the same as prior to the test.

Prior to actual calibration of the transducer resistance readings were taken across terminals A-B, A-C, and B-C (see Figure B-1) and compared against the resistance readings taken across the same terminals of an identical unirradiated transducer. No open circuits were found and within the accuracy of the ohmmeter used, resistances obtained from the irradiated transducer were identical to those obtained from the unirradiated transducer. Since the experiment was terminated after an open circuit was detected in the transducer circuitry at the recorder instrument panel this indicates that the failure actually occurred in the lead wires and not within the transducer itself. The break in the lead wires is thought to have occurred at 44,000 MWd/Te during removal of the capsule from the reactor for interim neutrography.

Calibration of the transducer was carried out with the same instrumentation used during the experiment with the aid of the calibrating fixture shown in Figure D-12. Calibration was carried out on each of three chart recording scales (50-mV, 100-mV, and 1-V full scale) and compared with the calibration curves obtained for the unirradiated transducer. Results of the calibrations are shown in Figures D-13, D-14, and D-15 respectively for the 50-mV, 100-mV and 1-V recording scales. The results indicate that the transducer was unaffected by the neutron irradiation within the accuracy of the recording instrument.

Figure D-12. Transducer Calibration Fixture

Figure D-13. Calibration of Transducers on 50-mV Recorder Scale

Figure D-14. Calibration of Transducers on 100-mV Recorder Scale

Figure D-15. Calibration of Transducers on 1-volt Recorder Scale

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