Atomic Energy of Canada Limited

A COLLAPSE MODE OF FAILURE IN POWDER-FILLED FUEL ELEMENTS

Exp-NRX-20605

by

M.A. FERADAY and G.H. CHALDER

Chalk River, Ontario

January, 1964

AECL-1894

DISCLAIMER

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M. A. Feraday and G. H. Chalder

(Presented at a Symposium on Powder-packed fuel elements at Worcester, Mass. November, 1963)

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SYNOPSIS

Two swaged fuel elements containing crushed, fused UO_2 powder were irradiated in a pressurized water loop at high heat ratings ($\int K d\theta = 48$ w/cm). The fuel elements were 2.0 cm in diameter and were sheathed in nickel-free Zircaloy-2 of 0.038 cm thickness.

One element failed when the sheath ruptured at the top of a longitudinal ridge in the sheath after a burn-up of approximately 2550 MWd/TeU.

No evidence was found that outgassing of the UO_2 contributed to the failure. Dimensional and structural changes observed in the fuel elements led to the conclusion that ridging of the sheath resulted from the action of coolant pressure on the diametral clearance formed by sintering and shrinkage of the UO_2. Failure resulted due to severe local deformation accompanying one or more power cycles following ridge formation.

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1. Introduction

Earlier irradiations of swaged fuel elements showed that the expansion of this type of element was less than that of elements containing sintered UO_2 pellets at the same heat rating[1]. Those tests were performed in unpressurized water coolant in the Hydraulic Rabbit facility in NRX at sufficiently high heat ratings to cause central melting of the swaged UO_2 ($K(T_s, T_o) = 70$ w/cm)*. Concurrently, autoclave testing of swaged fuel elements having thin cladding showed the UO_2 powder afforded sufficient support to the cladding to avoid collapse at reactor coolant pressure and temperature. These factors indicated that powder-filled fuel elements might be attractive in conditions where sheath deformation could be a problem with pellet fuel.

The present test was undertaken with the object of confirming the behaviour of elements containing swaged UO_2 fuel in thin Zircaloy cladding at high heat ratings ($K(T_s, T_o) = 48$ w/cm) in pressurized water coolant[3].

2. Fabrication of the Elements

Two elements designated DAV and DAW were fabricated for the test, each was 2.0 cm in outside diameter and had a UO_2 fuel length of 15 cm. The sheathing material was nickel-free Zircaloy-2 of 0.038 cm thickness.

The fabrication flowsheet is summarized in Fig. 1. Fused UO_2 (Batch P 108) of enrichment 1.96 wt % U-235 in uranium was heated in cracked ammonia at 1650°C for two hours, a procedure which had been shown to reduce the nitrogen content to a low value (< 50 ppm). The heat treated UO_2 was crushed and screened to provide a -16 mesh powder which was packed into Zircaloy tubes (Batch A6, Lot 63) using a pneumatic hammer[4]. The packed tubes were swaged using a 4-die machine through an area reduction of 27% in 2 passes. Each swaged rod provided fuel for one element, the end sections of the rod being retained as samples.

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* $K(T_s, T_o)$ represents $\int_{T_s}^{T_o} K(\theta)\, d\theta$ for convenience in typography. K is the thermal conductivity of UO_2 at temperature θ, subscripts s, sin, g, m and o to the limits of integration refer to the temperatures of the surface, the outer limit of sintering, the outer limit of discernible grain growth, the limit of melting and the centre of the fuel respectively. For fuel elements of similar material and of the same surface temperature, the integrated conductivity provides a measure of the temperature at these positions within the fuel. The derivation of this expression is discussed more fully elsewhere.[2]

After welding on vented end plugs, the elements were vacuum annealed at 750°C to recrystallise the cold worked structure of the Zircaloy and to dry the UO_2. The vent holes were finally sealed in a helium atmosphere. Routine dimensional measurements were taken[5]; helium leak testing and autoclaving of the completed elements revealed no unusual features.

A summary of fuel element data is given in Table 1. Sheaths taken from sample sections of the swaged rods showed no defects on microexamination. Analysis of the contained UO_2 gave an O/U ratio of 2.007, spectrographically detected impurities (Table 2) totalled some 600 ppm, iron and molybdenum being the principal contaminants. The volume of permanent gas evolved from a sample of the heat treated UO_2 at 1100°C was 0.018 cm^3/g measured at STP.

3. Irradiation of the Elements

The test was conducted in the X-2 and X-6 loops of the NRX reactor and was of some $4\frac{1}{2}$ months duration spread over a period of some 9 months. The irradiation history is summarised in Table 3. During each period of irradiation, other fuel elements besides DAV and DAW were present in the loop.

The elements were removed from the reactor twice during the irradiation and inspected and dimensioned before reinsertion. Results from these inspections will be discussed later.

When delayed neutron monitors indicated a failure, after approximately 2550 MWd/TeU burn-up of the fuel, the specimens were removed from the reactor and ultimately to a hot cell for post-irradiation examination.

4. Post Irradiation Examination

4.1 General

The defect was located in element DAW (Figure 2) and consisted of a split following the peak of a longitudinal ridge in the sheath, the edge of the ridge being visible by the strain marks (see arrows) on the oxidized Zircaloy surface.

4.2 Dimensional Changes

Both elements were measured to determine dimensional changes. DAV showed no change in sheath length after irradiation, while DAW had an increase in length of 0.023 cm. Figures 3 and 4 are plots of continuous diameter measurements taken along the full length of each fuel element, at three angular positions (0°, 120° and 240°) before and after each irradiation cycle. Figure 5 shows plots of a continuous diameter measurement taken around the circumference of DAW after failure at different distances (e.g., 1.27 cm) from a cut that was made through it. These diameters were plotted directly in the upper graph and then replotted as a longitudinal trace in the lower graph to augment the diameter traces in Figure 4 since the latter did not happen to occur right at the ridge and therefore do not show the full extent of the deformation.

These measurements show that some ovality developed in element DAV after the first irradiation cycle and persisted at subsequent examinations. There appears also to have been a net contraction of the element during irradiation of 0.002 to 0.005 cm. Element DAW exhibited about twice the ovality of DAV in the intermediate examinations and similar contraction. After failure, however, DAW had bulged near the ball end. The extent of bulging is illustrated in the lower graph of Figure 5 and shows the maximum distention occurred at the mid point of the defect, about 0.015 cm averaged around the diameter. The upper graph of Figure 5 shows the large single-lobe type of ridge present in the sheath along the length of the defect, with smaller double-lobe type ridges in the adjacent parts of the sheath.

4.3 Results of Gas Puncture Test

The sheath of DAV was punctured under vacuum and the gas in the element collected and analysed (See Table 4).

The amount of fission Xenon collected corresponds to about 30% of that generated in the irradiation. The amount of helium found is approximately 60% of the calculated free volume in the element at STP before irradiation.

Measurement of the gas evolved from an unirradiated sample of the UO_2 (See Section 2) corresponds to a total volume of 7.7 cm^3 associated with the weight of fuel in element DAV. Less than 10% of this volume (0.65 cm^3), measured as air and residuals, was collected from the irradiated element.

Based on a calculated free volume of 4.5 cm^3 in the unirradiated element, the total gas collected represents an internal pressure of less than 4 atm. at room temperature.

4.4 Examination of Fuel Cross Sections

Both specimens were sectioned with a tube cutter and the condition of the fuel was examined with a low power stereomicroscope. (See Table 5). Figure 6 is a cross-section of DAW at the point of failure, while Figures 7 and 8 show other sections of DAW and DAV, respectively.

Several cross sections of the fuel elements were also examined at a higher magnification after being impregnated and polished.

The cross sections of the irradiated fuel in Figures 6 - 8 indicate the extensive structural changes which have occurred. A small central void existed in both elements, generally surrounded by regions of columnar grains, equi-axed grains, some sintered UO_2 and finally a thin outer ring of unchanged UO_2 powder. A central core observed in some sections of DAW, in Figure 7 for instance, was strongly indicative of melting.

Micro-examination of cross sections of the sheath of element DAW showed a structure of heavily twinned grains of α-Zirconium near the failure and relatively twin-free equi-axed grains of average grain size near 40 μm in the remainder of the tube. The hydride concentration was generally low with the exception of one region near the failure in which a layer of hydride had formed on the inside of the sheath. (Figure 9). The sheath of element DAV consisted of twin-free α-Zirconium with few hydrides.

Both sheaths exhibited a reaction layer on their inner surfaces some 6 μm in thickness, penetrated by numerous microcracks. (Figure 10). Annealing tests on additional samples from swaged rods indicated that the layer was oxygen-rich Zircaloy formed by reaction of the sheath with the UO_2, or with water contained in it, during the pre-irradiation annealing of the elements. The microcracks were transgrannular, indicating they were formed on cooling after annealing, probably due to restraint imposed on the sheath by the contained UO_2[6].

4.5 Determination of Heat Ratings

Owing to the design of the elements, it was not possible to incorporate cobalt flux monitors over the fuel. Determination of overall heat rating, $K(T_s, T_o)$, was therefore made from measurements on flux monitors incorporated in other elements in the same loop assembly and from a knowledge of the axial flux distribution in the loop. The results given in Table 6, which were checked against calorimetric measurements of total heat output from the loop, are considered to be accurate to ± 10%. They show that the overall heat rating $K(T_s, T_o)$ of the elements varied between 35 and 56 w/cm during the course of the irradiation, the differences arising from changes in reactor flux and specimen location within the reactor.

Values of the integrated conductivity to sintering, $K(T_s, T_{sin})$, were calculated from time average heat ratings for the whole period of the irradiation, since this phenomenon is time dependent. The value of the integrated conductivity to melting, $K(T_s, T_m)$, was determined from a peak heat rating which occurred in element DAW early in the first cycle of irradiation. These results were normalized to a fuel surface temperature of 400°C and are included in Table 6. The fuel to sheath heat transfer coefficient was assumed to drop from 1.4 w/cm^2 °C at the start of the irradiation to 1.0 w/cm^2 °C at the end, to allow for dilution of the helium filling gas with fission product gases. The fuel-sheath contact pressure was taken to be the loop pressure (100 kg/cm^2).

The average values of the integrated conductivity to grain growth (K (400, Tg)) were determined using a method due to MacEwan[7] and assuming the same grain growth temperatures for crushed, fused UO_2 as for sintered pellets of UO_2. Other assumptions involved in the calculations are given in Table 6.

5. Discussions

5.1 Failure Mechanism in DAW

Dimensional measurements at intermediate stages of the irradiation show DAW developed more ovality than DAV and that both elements contracted in diameter. After failure, DAW exhibited a severe longitudinal ridge and had increased in all diameters (bulged) near the failure.

Both elements were autoclaved at 300°C and 87 kg/cm^2 before irradiation and exhibited no dimensional changes. It is suggested that redistribution of porosity in the UO_2 as the result of sintering and grain growth (and, in the case of DAW, melting) increased the effective fuel-sheath clearance, allowing sheath collapse and the formation of a longitudinal ridge under coolant pressure. It seems likely that the ridge was initiated on a reactor shut-down when the fuel was cool and contracted. Subsequent start up of the reactor would produce stressing at the peak of the ridge and failure in one or more reactor cycles. The reason for ridge formation and subsequent failure in DAW and not in DAV is probably due to its higher heat rating, as evidenced by examination of fuel cross-sections, and its slightly thinner sheath.

Oxidation of the inner surface of the sheath and the associated microcracks are not thought to have been a prime cause of failure since they occurred also in element DAV. However, by acting as stress raisers, the microcracks probably accelerated the failure.

Bulging of the sheath of DAW could have occurred prior to failure due to internal gas pressure or to expansion of the UO_2. The quantity of gas found in element DAV indicates that gas pressure was not the cause. Since neither element showed any sheath expansion at intermediate examinations, and DAV was still stable subsequent to irradiation, it is suggested the bulging in DAW occurred after failure.

Loop records show that the coolant water flow was continued for four hours after DAW failed and the reactor was shut down. Shortly after the coolant flow was stopped and some water drained from the test section, there was a sudden increase in activity, indicating further possible rupture. The loop was then repressurized and loop flow restarted. It is suggested that water entered the element through a small defect on the shut down following the failure. When cooling was stopped and the coolant pressure removed, decay heating in the fuel caused a rise in temperature in the element and evaporated the water present. Due to the small size of the defect, or to its becoming plugged with loose UO_2, sufficient internal pressure was developed in the element by the steam to cause bulging and propagation of the defect. It is calculated that saturated steam at a temperature of about 320°C would exert sufficient pressure (114 kg/cm^2) to plastically deform a sheath of thin dimensions and of yield strength 3520 kg/cm^2 (50,000 psi) at that temperature.

The failure mechanism proposed is related to the fuel element (and sheath) geometry, the fuel density, the element heat rating in so far as it produces shrinkage of the fuel, and the coolant pressure. It may also be related to the number of thermal cycles to which the element is exposed in its in-reactor life. No information is available from the present test to indicate the relative importance of these factors in precipitating failure, nor can safe conditions for operation of this fuel design be predicted, except by using a free-standing sheath.

It is felt that the implication of these results is particularly important for large diameter elements, tubes for instance, where the thickness of a free-standing sheath would be unacceptable in most reactor systems.

5.2 Dimensional Changes

The net contraction of 0.1 - 0.2% of diameter observed after irradiation of element DAV (See Section 4.2) is to be compared with an expansion of some 0.5 - 1.0% observed in pellet filled elements at similar heat rating.[8] While this behaviour would be valuable in limiting sheath strain in highly rated fuel elements, the attendant problem of ridge formation and subsequent failure in the powder fuel (Section 5.1) would require solution for collapsible sheathing.

5.3 Gas Puncture Results

The release of fission gas from element DAV is compared to releases measured from pellet fuel of different densities over a range of heat ratings in Table 7. The 30% fission gas release from DAV is not inconsistent with that anticipated from pellet fuel of the same density (10.0 g/cm^3). It is, however, about twice the release expected from typical high density pellets (10.6 g/cm^3) at the same heat rating.

The low amount of residual gas observed on puncture testing compared to that found in an unirradiated archive sample of UO_2 is attributed in part to further outgassing during vacuum annealing of the element at 750°C before irradiation; the archive sample was not annealed. Additional gas may have been released by the UO_2 during the irradiation and readsorbed on cooling. The absence of any deleterious effect on the elements due to fuel outgassing during irradiation can only be associated with an upper limit on gas content of 0.02 cm^3/g.

5.4 Structural Changes in the Fuel

The observation of central melting in DAW was correlated with a peak heat rating experienced early in the first irradiation cycle to give a value of K $(400, T_m) = 52$ w/cm. This is within the error of measurement of the integrated conductivity to melting determined for swaged UO_2 in earlier short duration experiments (K $(400, T_m) = 57$ w/cm[1]. Although a higher overall rating occurred in the last cycle (K $(400, T_o) = 56$ w/cm), melting has been attributed to the earlier power peak for two reasons. Firstly, the flux distribution associated with the early peak would cause a high rating only in DAW, consistent with the absence of melting in DAV. Secondly, the improved thermal conductivity attributed to swaged fuel which has undergone a period of in-reactor sintering would increase the heat rating required to produce melting as the irradiation proceeded.

Observations of the heat ratings required to produce sintering and grain growth in those specimens can be compared to those found in an earlier irradiation of comparable duration on swaged elements containing crushed, sintered UO_2[11]. The values of K $(400, T_{sin})$ and K $(400, T_g)$ are respectively 13 w/cm and 28 w/cm for this test and 6 w/cm and 23 w/cm derived from the earlier test. The discrepancy of some 20% between the value for K $(400, T_g)$ may be attributed to differences in the temperature required to produce discernable grain growth in the two different materials, as well as the possible difference in their thermal conductivity at lower temperatures. The somewhat greater difference in the K $(400, T_{sin})$ values is believed to reflect in addition the difficulty of locating the limit of sintering in fuel cross-sections.

6. Conclusions

1. A longitudinal ridge in the sheath of element DAW resulted from the action of coolant pressure on the diametral clearance formed by sintering and shrinkage of the contained UO_2 fuel.

2. Failure of DAW occurred at the peak of the ridge due to severe local deformation resulting from one or more power cycles following ridge formation.

3. The microcracks on the inside of the sheaths of both elements were not the prime cause of failure in DAW but probably accelerated the failure by acting as stress raisers.

4. Failure occurred first in DAW rather than DAV due to the higher heat rating, producing more sintering and shrinkage of the fuel and thinner sheath of the former.

5. The fission gas release of one powder packed fuel element was similar to that of pellet filled elements at similar heat ratings and UO_2 density.

6. Powder-packed fuel elements containing properly degassed UO_2 exhibit less expansion than pellet fuel elements under similar irradiation conditions.

7. The results of this test indicate that the sheaths of powder packed fuel elements, having a high ratio of diameter to sheath thickness (50:1 in this test) and operating at high heat ratings, are afforded insufficient support by the fuel to prevent sheath collapse and subsequent failure in pressurized water coolant.

8. More experiments are required to define the limiting conditions to avoid failure for a particular fuel design.

7. Acknowledgements

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8. References

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TABLE 1

DESCRIPTION OF SWAGED ELEMENTS DAV, DAW

	SHEATH					FUSED URANIUM DIOXIDE						
Specimen	Material	Thickness (cm) (±0.004)	O. D. (cm)	Length (cm)	Swage Reduction (%)	Batch	Density Tap (g/cm³)	Density Final (g/cm³)	Enrichment U-235 in U (wt. %)	O/U Ratio	Length (cm)	Diameter (cm)
DAW	Zr-2*	0.037	2.0	18.03	27	P108	9.15	9.87	1.96	2.007	15.5	1.92
DAV	Zr-2*	0.040	2.0	18.00	27	P108	9.05	9.96	1.96	2.007	15.5	1.92

* Nickel free

TABLE 2

SPECTROGRAPHIC ANALYSIS OF FUSED UO_2 BATCH P108

Ag	*	Be	*	Cu	2.0	Nb	*	Ti	6.0	Zr	20.0
Al	15	Bi	*	Fe	350.0	Ni	40	V	*	Sr	*
Au	*	Ca	30.0	Mg	*	Pb	*	W	*		
B	0.8	Cd	<0.3	Mn	2.0	Si	2.0	Y	*		
Ba	2.0	Cr	20.0	Mo	180.0	Sn	*	Zn	*		

Notes: All values expressed as parts per million of uranium content.

* looked for but not detected.

TABLE 3

LOOP LOADING DIAGRAMS FOR THE FOUR PERIODS OF IRRADIATION OF ELEMENTS DAV AND DAW

	1. Irradiation Period Starting	21 March 1962	17 July 1962	24 Sept. 1962	22 Oct. 1962
	2. Loop	X-2	X-6	X-6	X-6
	3. Loop Pressure (kg/cm^2)	99.5	99.5	99.5	99.5
	4. Inlet Temperature (°C)	253	247	240	253
	5. Outlet Temperature (°C)	268	275	253	268
	6. Flow (l/sec)	0.63	0.76	0.64	0.63
	7. Reason for removal	Inspection	Inspection	Element FJZ added to string	DAW failed
Height above vessel bottom (cm.)				DMA	DMA
250				DMD	DMD
			DFN		
				DAV	DAV
200			DFM		
		DAV			
			DAV		
			CEZ_2		
150	Nominal ℄ of flux	CEW			FJZ
			CEY		
			DAW		
100		DAW	DFL		
				DAW	DAW
50				DMC	DMC
				DMF	DMF
0					

TABLE 4

ANALYSIS OF GAS FROM PUNCTURE TEST ON "DAV"

Air	0.16 cm^3	Fission Xenon	9.48 cm^3
Helium	2.73 cm^3	Residual	0.49 cm^3
Krypton	1.40 cm^3	Total Gas	14.26 cm^3

TABLE 5

APPEARANCE OF THE SWAGED IRRADIATED FUSED UO_2 IN ELEMENTS DAV AND DAW

Item	Element	Distance from Ball End (cm)	Diameter of central void or core (cm)	Diameter of grain growth (cm)	Diameter of Sintering (cm)	General Appearance
1.	DAV	1.9	-	1.2	1.59	Columnar grains radiating from centre; surrounded by a small layer of equiaxed grains, sintered UO_2 & an outer layer of undisturbed UO_2.
2.	DAV	9.5	0.2	1.4	1.66	Columnar grains radiating from a central void. Remainder as in item 1.
3.	DAV	12.1	0.17	1.3	1.68	As in item 2.
4.	DAV	15.2	0.12	1.3	1.62	Columnar grains radiating from much smaller void. Remainder as in item 1.
5.	DAW	2.54	0.60	1.3	1.72	A centre core with some porosity surrounded by columnar grains radiating out from the centre. This in turn was surrounded by some equiaxed grains of sintered UO_2 and an outer layer of undisturbed UO_2.
6.	DAW	4.44	0.5	1.4	1.59	As in item 5
7.	DAW	4.70	0.4	1.4	-	As in item 5
8.	DAW	5.72	-	1.4	1.68	Possible centre core or void with columnar grains radiating out from it.
9.	DAW	8.55	0.4	1.4	-	As for item 5 however, grains are less pronounced.
10.	DAW	9.2	0.3	1.3	1.60	Columnar grains radiating from a well defined central core which had a small void at its centre. Remainder as in item 5. See Figure 7.
11.	DAW	14.6	0.1	1.3	1.69	Columnar grains radiating from a very small central void. Remainder as in item 5.

TABLE 6

IRRADIATION DATA(1) FOR ELEMENTS DAV AND DAW

Period Starting	Element	Power(1) Output of Element (kw)	E. F. P. D. (2)	Power Cycles	Burnup(1) (MWd/teU)	$K(T_s, T_o)$ w/cm Average(1)	T_s(4) (°C) See Section 4.5	$K(400, T_o)$ w/cm Average(1)	$K(400, T_g)$ Average w/cm. See Section 4.5	$K(400, T_m)$ w/cm See Section 4.5	K(400, T_{sin}) w/cm
21 Mar. 1962.	DAV	10.24	26.08	19	682	50.2	383	49.7	-	-	-
	DAW	10.24			680	50.2	381	49.7	-	51.1	-
17 July 1962	DAV	9.30	23.94	10	568	45.5	377	44.9	-	-	-
	DAW	9.30			567	45.5	377	44.9	-	-	-
24 Sep. 1962	DAV	7.24	18.48	7	342	35.4	356	34.4	-	-	-
	DAW	7.66			362	37.6	358	36.6	-	-	-
22 Oct. 1962	DAV	11.32	32.10	8	930	55.6	430	56.2	-	-	-
	DAW	11.31			926	55.6	428	56.2	-	-	-
Total	DAV	-	100.6	44	2522	48.2(3)	-	-	29.0	-	13.6(3)
	DAW	-			2535	48.5	-	-	27.2	-	12.7

(1) The loop output was corrected to compensate for heat lost from the test section and gamma heating of the loop components. The output was then multiplied by $\frac{182}{185}$ to give the power produced in the fuel alone.

(2) Equivalent Full Power Days based on 42 MW reactor power.

(3) Time average values for the four cycles.

(4) In calculating T_s the film co-efficient for water was assumed to be 5 w/cm^2°C for the periods when the flow was 0.63 l/sec. and 5.6 w/cm^2°C for 0.76 l/sec. The thermal conductivity of Zircaloy was taken as 0.15 w/cm^2°C.

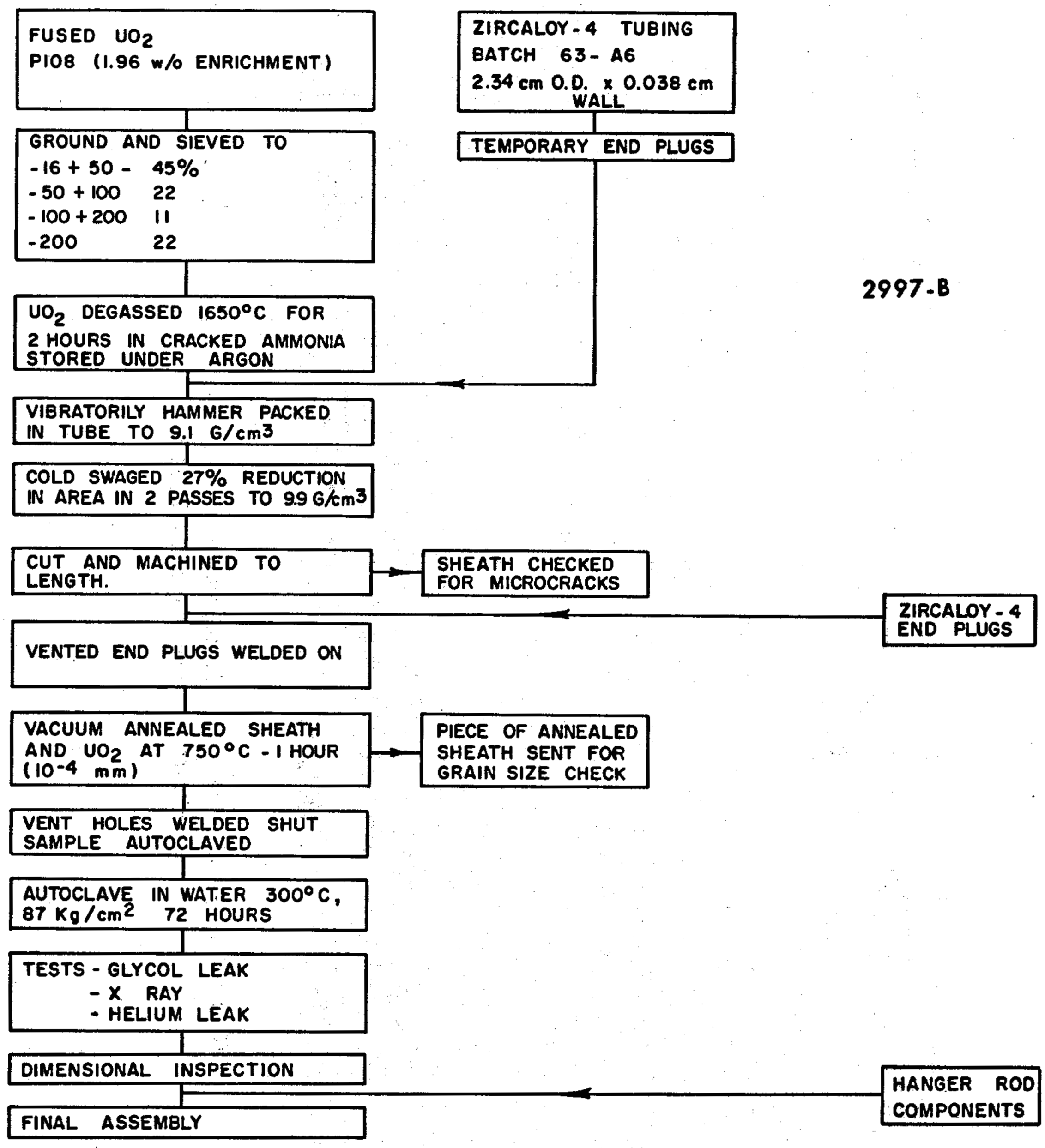
TABLE 7

FISSION PRODUCT GAS RELEASE VALUES

Experiment	Time Average K(400, T_o)	Fuel Density g/cm^3	Fission Gas Release %
NRX-2400 (9)	42 - 45	10.1	28 - 29
NRX-2800 (10)	42	10.2 - 10.4	22 - 24
NRX-21100 (8)	55	10.6	18
	40	10.6	5
NRX-20600 (this test)	48	10.0	30

FIG. I

FLOW SHEET FOR THE FABRICATION OF ELEMENTS DAV AND DAW (EXP - NRX - 206)



2997-B

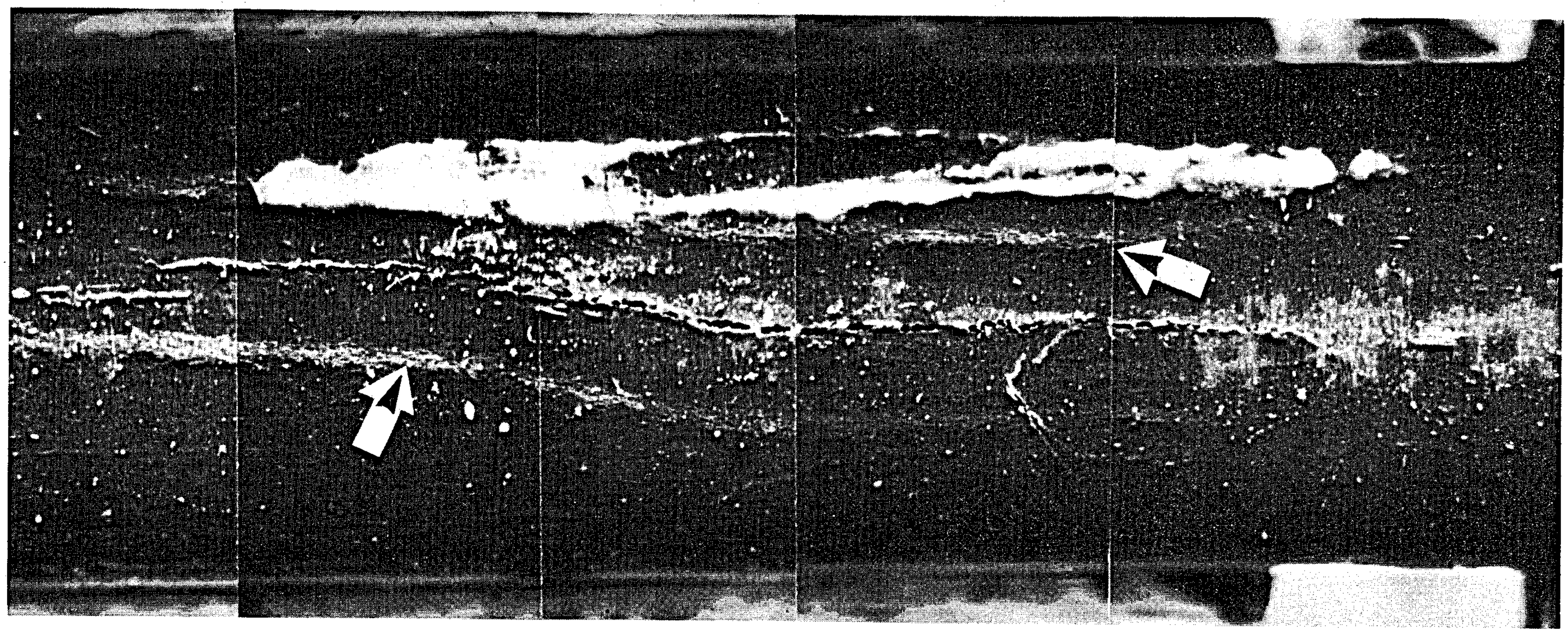


FIGURE 2 - Composite Photograph of the sheath rupture of element DAW (Photographs 7605 to 7610) X4.8 (approx.)

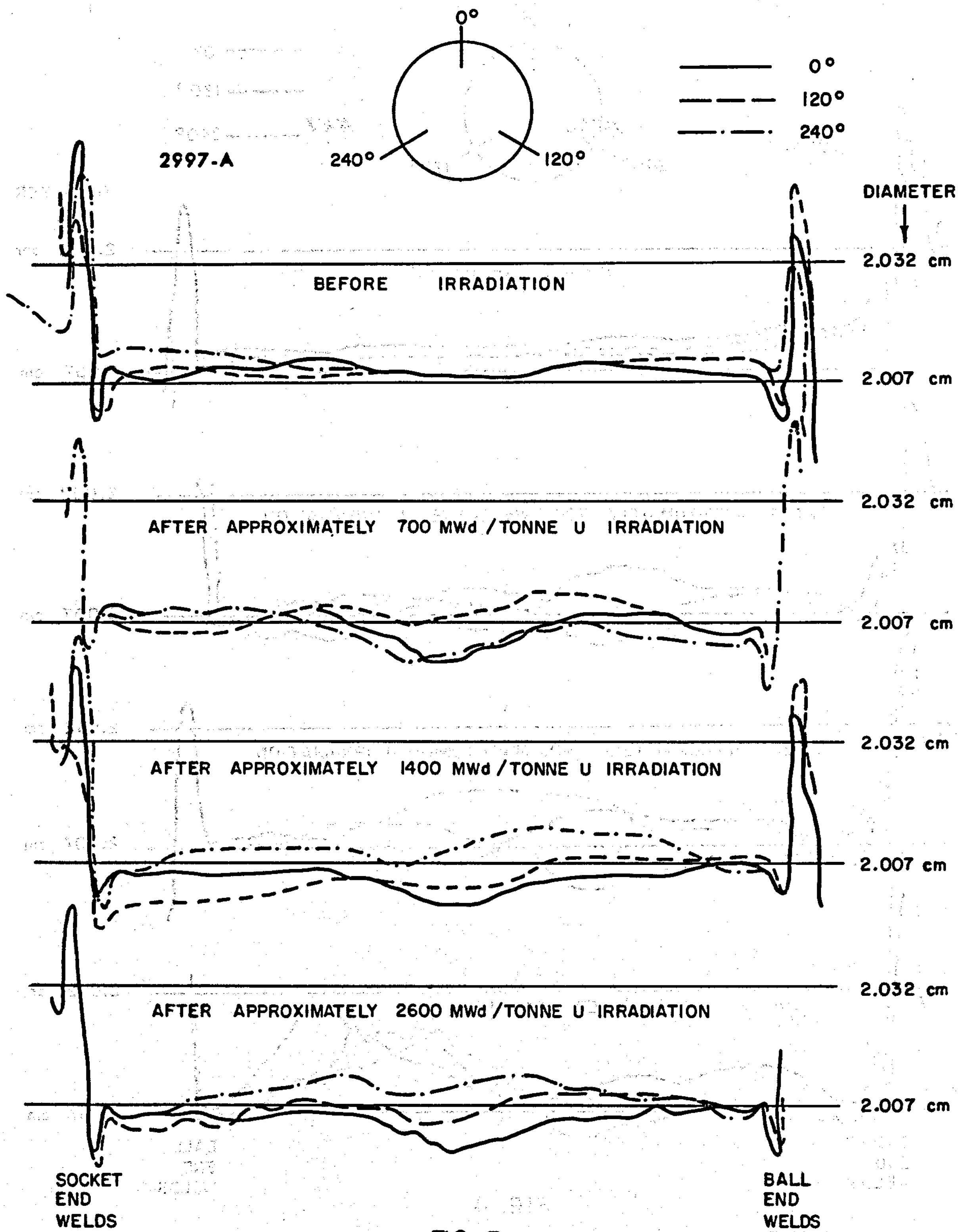


FIG. 3

VERTICAL DIAMETER TRACES OF ELEMENT DAV BEFORE AND AFTER IRRADIATION

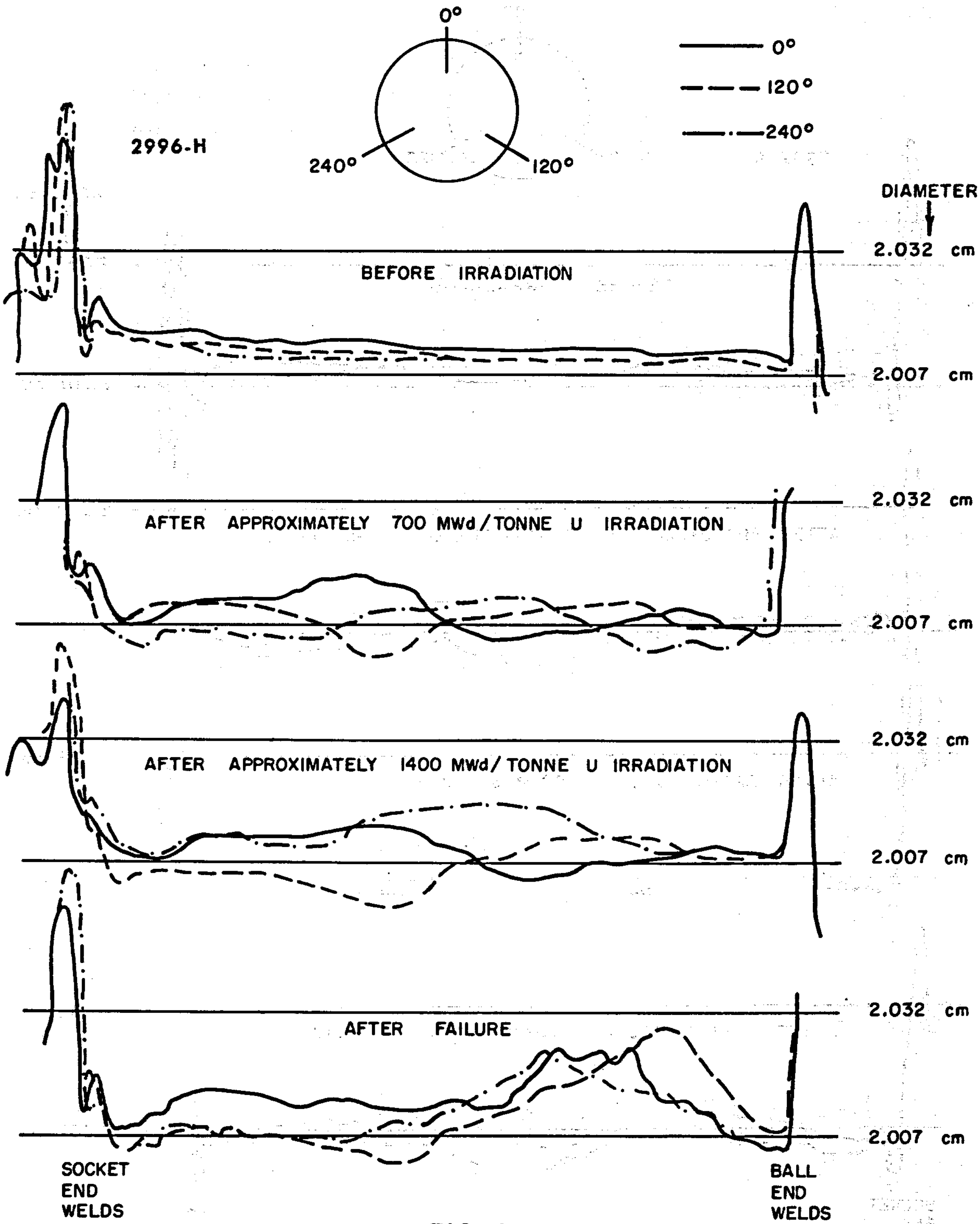


FIG. 4

VERTICAL DIAMETER TRACES OF ELEMENT DAW BEFORE AND AFTER IRRADIATION

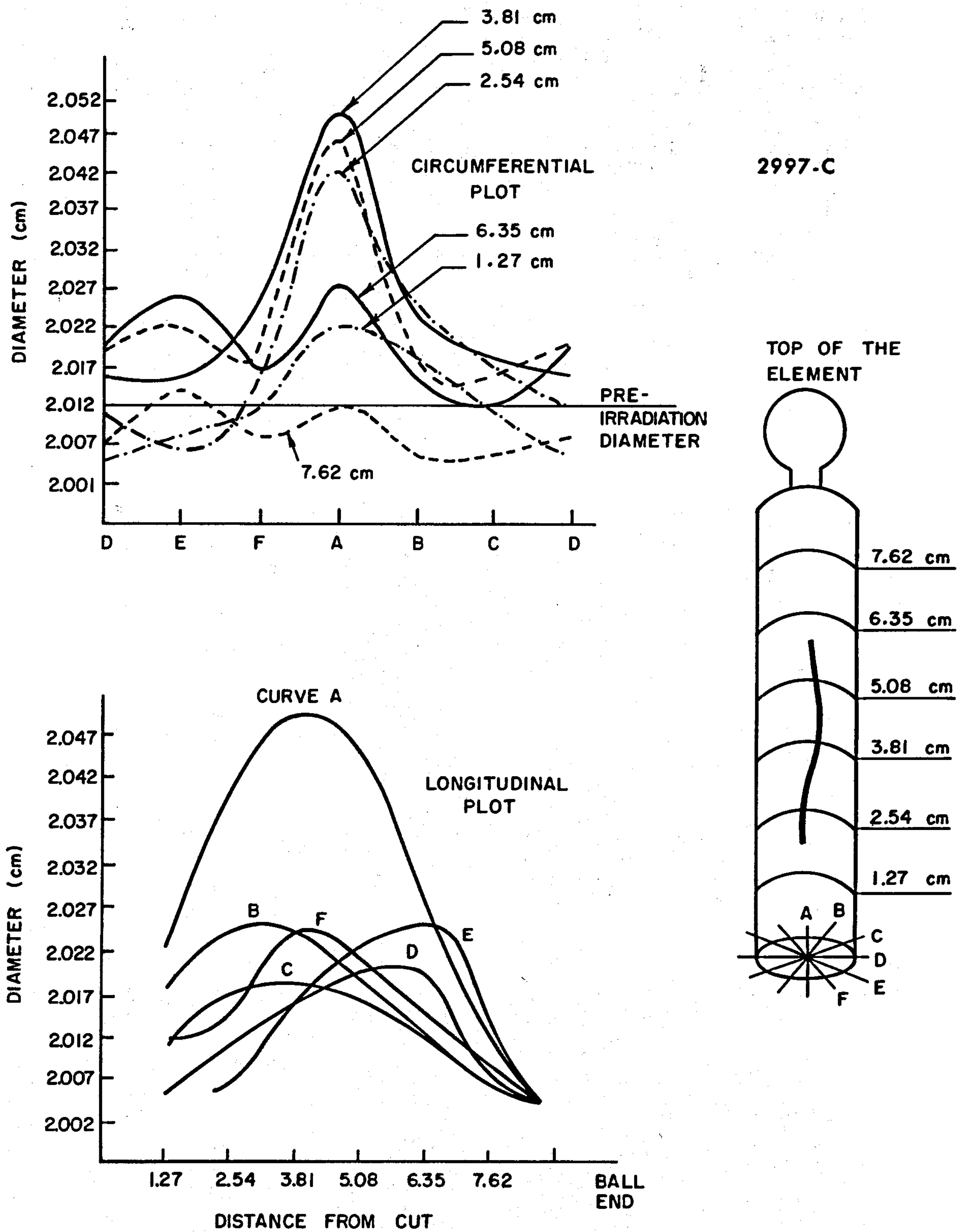


FIG. 5

PLOTS OF CIRCUMFERENTIAL DIAMETER TRACES OF DAW AFTER FAILURE

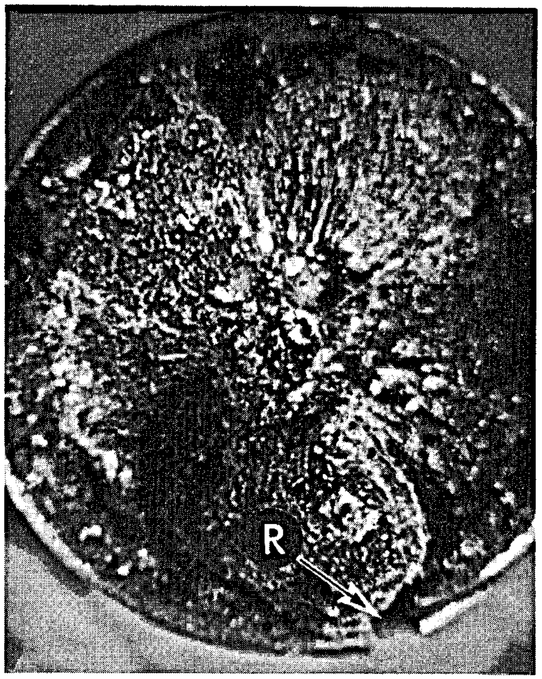


FIGURE 6 X 4 (approx.)

Element DAW at Point of Failure

Photo 7687

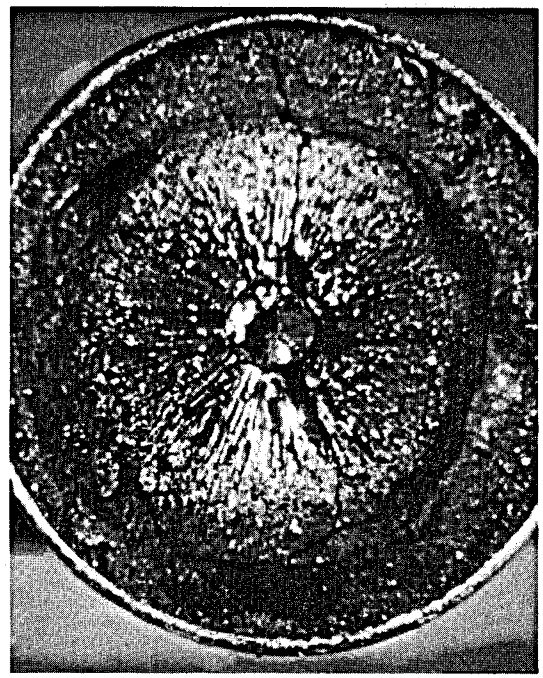


FIGURE 7 X 4 (approx.)

DAW after Failure. 9.2 cm from Ball End

Photo 7611

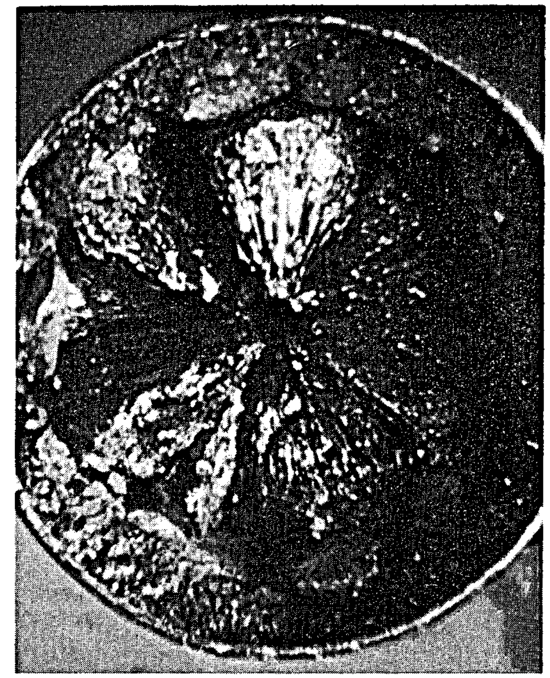


FIGURE 8 X 4 (approx.)

DAV after approximately 2600 MWd/ Tonne U. Irradiation 9.5 cm from the Ball End.

Photo 7680

Figure 9 (X5 - B3) X 250
Isolated Area of High Hydride Concentration on I. D. Near Ridge of Element DAW (5).

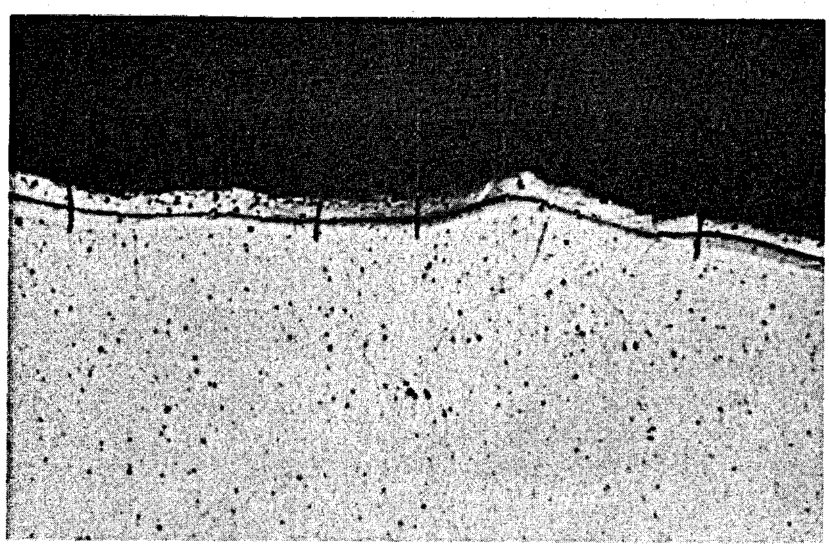


Figure 10 (X5 - A2) X 500
Oxygen Rich Layer and Fine Cracks on the I. D. of Element DAW.

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