Atomic Energy of Canada Limited

POST-IRRADIATION EXAMINATION OF THE FIRST SAP CLAD UO_2 FUEL ELEMENTS IRRADIATED IN THE X-7 ORGANIC LOOP

CRFD-1084
(Exp-NRX-5806)

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R.D. MacDONALD and K. ASPILA

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SYNOPSIS

Seven fuel elements composing the first in-reactor test at Chalk River of SAP sheathing were irradiated in the X-7 organic loop. Activity, denoting a fuel failure, was detected in the loop coolant immediately after reactor start up; the fuel string was consequently removed from the loop nine hours later. Leak tests disclosed that five of the seven elements were defective. Inspection of the specimens showed essentially no change in element dimensions. Practically no organic fouling film was observed on the surface of the SAP cladding; organic coolant was found inside four of the defective elements. The appearance of the UO_2 fuel was consistent with the irradiation time and the heat ratings achieved during the test.

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A. INTRODUCTION AND OBJECTIVES

SAP* was chosen as the sheathing material for fuel elements in an organic cooled power reactor because of its good neutron economy, high strength at elevated temperatures and low susceptibility to hydriding. However, little was known about the irradiation behaviour of SAP sheathing in contact with hot flowing organic liquids. In September 1959, Atomics International (AI), Canadian General Electric (CGE), and Atomic Energy of Canada Limited (AECL) entered into a co-operative agreement to further SAP technology and to gather irradiation data on this material. The X-7 organic loop had just become available for in-pile experimentation at Chalk River, and it was proposed that an early test should involve fuel elements clad with SAP.

A test string of seven SAP clad UO_2 fuel elements was proposed by Hatton, Cracknell and Page(1) for the third loading of the X-7 loop. The fuel elements were to be fabricated by AI to specifications set by CGE. The objectives of the test, as listed in the proposal were:

1. To irradiate SAP-clad fuel under conditions similar to those anticipated in an organic cooled power reactor.

2. To obtain information on erosion and filming of SAP sheathed, organic cooled fuels.

3. To conduct heat transfer studies; particularly to estimate values of the film coefficient for the organic coolant.

4. To determine the extent of pyrolytic and radiolytic damage to the coolant.

B. FABRICATION

1. Uranium Dioxide Pellets

The UO_2 pellets were fabricated by the Davison Chemical Co. from oxide with an enrichment of 3.23 wt % U-235 in U. A binder of polyvinyl alcohol was used in the green pressing of the pellets. The sintered density, calculated from weights and volumes of the individual compacts, ranged from 9.98 to 10.2 g/cm^3. Metallographic examination of representative pellets at Chalk River revealed a non-homogeneous oxide structure consisting of an outer high-density skin and an inner porous region(2).

* SAP-Sintered Aluminum Product

Davison explained this porosity as being caused by too rapid sintering, resulting in the outer shell of the pellet becoming densified before the interior of the pellet was completely heated(3). The shrinkage of the centre material when sintered was towards the fully densified outer shell forming a porous region in the centre of the pellet.

2. Cladding and End Plugs

The sheathing material was M-257 (APM)* impact extruded by Alcoa with a tube wall thickness of approximately 0.051 cm (0.020 in.). Metallographic examination by CGE showed that the surface of the tubing was badly pitted with stringers of iron-rich inclusions(4). However, as this was the only material available, it was necessary to use it for the sheathing of the fuel charge.

The end plugs were machined from the aluminum alloy AA 6061 (equivalent to Alcan 65S) and electro-plated with silver to improve bonding.

3. Assembly and Testing of the Elements

The elements were fabricated at the Canoga Park facilities of AI. Stack lengths of eight UO_2 pellets were loaded into the tubing. Dished pellets (0.036 cm (0.014 in.) at one end) were used in three elements, while the remaining four elements contained flat-ended pellets. The end plugs were pressure bonded (105 to 211 kg/cm^2 (1500 to 3000 lb/in^2)) to the sheaths in a helium atmosphere at a temperature of 590°C (1094°F). Two aluminum bands, 0.051 cm (0.020 in.) thick, were spot welded to the sheaths of specimens AHH, AHK, AHL and AHO to hold the sheath thermocouples (see Figure 1).

After the thermocouple bands were attached, all specimens were leak tested by thermal cycling between 150°C (302°F) and 480°C (896°F) while sampling for helium gas. Small helium signals were recorded for elements AHH, AHK, AHL and AHO, but as the signals decreased sharply with time, they were assumed to be due to helium trapped in the weld porosity and under the bands(5).

Pre-irradiation dimensions of the elements are included in Table 1.

* APM (Aluminum Powder Metallurgy) is the name given by U.S. Manufacturers for Sintered Aluminum Product (SAP).

4. Instrumentation and Flow Tube

Chromel-Alumel thermocouples were attached to those elements with the aluminum bands. All elements were mounted by means of a spider ring inside a thick walled 0.76 cm (0.3 in.) aluminum flow tube, 3.30 cm (1.30 in.) outside diameter. The annular gap between the flow tube and the fuel was approximately 0.20 cm (0.080 in.) giving a proposed coolant velocity of 91.4 cm/s (30 ft/s) at the normal loop flow rate of 57. litres/min (15 gal (US)/min.)

Thermocouples to measure the temperature of the coolant upstream and downstream of the specimens were attached inside the flow tube. A more complete description of the thermocouple instrumentation is provided by Delaney(6).

C. IRRADIATION HISTORY

The flow tube, containing the fuel, was inserted into the X-7 loop during the 17 October 1960 shutdown. Upon reactor start-up at 0707 hours 20 October 1960 to a power level of 15 MW, the gamma monitor recorded a count-rate greater than 25,000 c/min; this was indicative of a probable fuel failure. The reactor power was raised in steps to a maximum of 35.4 MW at 1427 hours 20 October 1960. Each increase in reactor power was followed by an increase in the activity of the loop coolant. Because of this high activity in the loop, the test was stopped at 1555 hours 20 October 1960 and the test section removed for preliminary inspection.

Reactor and loop conditions during the first SAP test are summarized in Table 2 and Figure 2. Delaney(6) has prepared a plot of reactor power versus test-section heat output which is included as Figure 3. The test-section heat output derived from this graph was used to calculate the heat ratings of individual fuel elements (see Table 3).

D. OBSERVATIONS

The fuel elements were removed from the flow tube and examined under a stereomicroscope for defects; none were observed. The sheathing contained many small surface pits and inclusions generally oriented parallel to the axis of the specimens and similar to those observed prior to irradiation. The elements were leak tested using two methods: a vacuum pumping at 300°C (572°F) with sampling for the activity of fission products; and a liquid nitrogen-alcohol dip. The results of these tests have been described in detail by Bain(7) and are summarized below:

Samples AHH, AHK, AHL } Contained a small hole at the position of the spot weld securing the middle thermocouple band to the sheath.

Samples AHJ } AHM } Were defective at the spider end pressure bond between the sheath and end plug.

AHN } AHO } Were not defective

After leak testing, measurements of specimen diameters, lengths, and the heights of circumferential ridges were recorded. These are compared with the corresponding pre-irradiation measurements in Table 1. No measureable amount of decomposed organic coating (fouling film) was observed on the sheaths. The aluminum thermocouple bands were removed from all elements with the exception of AHO to permit more accurate length measurements.

All elements were sectioned with tubing cutters to examine the disposition of the uranium oxide and the inside surface of the sheathing. The principal observations were:

1. Organic coolant had penetrated into four of the defective elements. Solidified coolant was observed on the inside surfaces of end caps, at gaps between pellets and as droplets on the inside of the sheath (Figure 4).

2. No grain growth or coalescence of pellet faces was observed. Pellet centres appeared porous similar to the centres of unirradiated compacts. A network of fine cracks extended throughout the region of porosity in the irradiated samples.

3. The UO_2 pellets were randomly cracked. Dark concentric rings appeared on the pellet ends (see Figure 5) and on several fracture surfaces. A typical fuel cross-section is shown in Figure 6.

4. The cracking pattern of the pellet was outlined by a deposit on the inside surfaces of the sheath and on several end caps (Figure 7).

Metallographic samples of the defected sheaths were taken for examination by AI and AECL.

E. DISCUSSION

1. Heat Ratings

Cobalt monitor and burnup data have little meaning for the first SAP test because of the short irradiation time and the continually shifting reactor power. The approximate heat ratings tabulated in Table 3 are estimated from the average and maximum values of the loop calorimetric heat output.

2. Fouling Film

The lack of an observable film is probably due to the short duration and low reactor power during the test[8].

3. Failure of the Fuel Elements

Although all elements were leak tested and considered sound after the attachment of the thermocouple bands, immediately upon reactor start-up activity was detected in the loop coolant denoting a defective element in the fuel string. Damage may have occurred during shipment to Chalk River or at the time of installation of the test string into the loop. Furthermore, the sheaths of the elements would have been subject to both thermal and mechanical stresses prior to reactor start-up when the coolant was raised to its operating temperature of 370°C (698°F) and the system pressurized to 16.1 kg/cm^2 (215 lb/in^2). It seems probable that the spot welds holding the bands to the sheath (the location of the failure in three elements) may have been points of initial weakness requiring only very small stresses to cause a rupture. Metallographic examinations of samples of pressure-bonded end caps show that discontinuities in the bonding could occur[9]. Thermal stresses in operating fuel elements could propagate these flaws until failure of the end closure occurred.

4. Dimensional Changes

Within the limit of experimental error the lengths and diameters of the SAP samples were unchanged from the pre-irradiation measurements.

5. UO_2 Fuel

The appearance of the UO_2 (random cracking and no grain growth) was consistent with what would be expected from the level of reactor power and the duration of the test.

F. CONCLUSIONS

1. Five of the seven elements failed on reactor start-up. Three were ruptured at the spot weld holding the middle thermocouple band to the sheath and two had defective end closures.

2. No organic fouling film was present on the surfaces of the SAP elements. Organic coolant was found inside four of the defective elements.

3. The lengths and diameters of the SAP specimens had not changed.

4. The appearance of the uranium oxide was consistent with the heat ratings and the time of irradiation.

5. Spot welding of straps to the SAP cladding is not recommended as a method of attaching sheath thermocouples.

REFERENCES

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5. Lew, D. E. - Private communication to R. D. MacDonald.

6. Delaney, R. D. and Allison, G. M. - The First Irradiation of SAP-Clad UO_2 in the X-7 (Organic) Loop - Exp-NRX-5805 - July, 1961.

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8. Charlesworth, D. H. - Status of Fouling Experience in Organic-Cooled Systems at A.E.C.L. - CEI-132, May, 1961.

9. Evans, W. - Memorandum to M. B. Watson - Examination of Diffusion Bonded End Closures in M257 Alloy Tubing. October 28, 1960.

TABLE 1

DIMENSIONAL CHANGES FOR FIRST SAP FUEL ELEMENTS

Specimens (a)	Clearances (in.) (c)		Diameter (in.) (b)				Length (in.) (b)			Circumferential Ridges	Remarks (d)
	Dia.	Axial	Position of Measurement	Pre-Irradiation	Post-Irradiation	Diff.	Pre-Irradiation	Post-Irradiation	Diff.		
AHH (Top)	0.005	0.090	Spider	0.549	0.549	0.000	7.840	7.837	-0.003	Ridges too faint to be measured	Defective One T/C intact
			Middle	0.548	0.548	0.000					
			Lug	0.5495	0.548	-0.0015					
AHJ	0.005	0.082	S	0.5485	0.5495	+0.001	7.807	7.802	-0.005	Ridges too faint to be measured	Defective
			M	0.548	0.5485	+0.0005					
			L	0.550	0.5495	-0.0005					
AHK	0.0045	0.082	S	0.548	0.547	-0.001	7.838	7.838	0.000	Ridges too faint to be measured	Defective One T/C intact
			M	0.547	0.547	0.000					
			L	0.5465	0.548	+0.0015					
AHL	0.005	0.097	S	0.549	0.548	-0.001	7.828	7.824	-0.004	Average ridge height 0.0015 in.	Defective Both T/C intact
			M	0.548	0.549	+0.001					
			L	0.547	0.5485	+0.0015					
AHM	0.005	0.030	S	0.5495	0.5475	-0.002	7.827	7.831	+0.004	Average ridge height 0.003 in.	Defective Pellets dished 0.014 in. one end
			M	0.5485	0.5475	-0.001					
			L	0.5485	0.548	-0.0005					
AHN	0.005	0.019	S	0.5495	0.548	-0.0015	7.814	7.812	-0.002	Average ridge height 0.002 in.	Pellets dished 0.014 in. one end
			M	0.5495	0.549	-0.0005					
			L	0.549	0.5495	+0.0005					
AHO (Bottom)	0.005	0.032	S	0.5485	0.548	-0.0005	7.835	7.842	+0.007	Ridges too faint to be measured	Pellets dished 0.014 in. one end. Both T/C broken
			M	0.548	0.5485	+0.0005					
			L	0.5485	0.548	-0.0005					

(a) Specimens listed in their loading order in loop. Centre line of flux was located at centre of AHL
(b) Diameter measurements accurate to ± 0.001 in. Length measurements accurate to ±0.005 in.
(c) Sheath thickness for all elements 0.020 in.
(d) Thermocouple (T/C) elements contained two sheathed thermocouples held by two aluminum bands.

TABLE 2

LOOP OPERATING CONDITIONS (0707 h Oct. 20, 1960 to 1555 h Oct. 20, 1960)

Reactor Power	Average 28.2 MW Maximum 35.4 MW
Moderator Height	253 cm at 1240 h 20/10/60
Operating Time	8.75 h approx. 0.63 h at max. power
Integrated Reactor Power	10.2 MWd
Thermal Cycles	1
Outlet Coolant Temperature	397°C (746°F) at 31.5 MW
Temperature difference across Fuel (ΔT)	23°C (41°F) at 31.5 MW
Outlet Pressure	16.1 kg/cm^2 (215 lb/in^2 gauge)

TABLE 3

HEAT RATINGS OF FIRST SAP FUEL ELEMENTS

Specimen	Linear Heat Output (W/cm)		Surface Heat Flux Sheath to Water				$\int_{T_s}^{T_o} k d\theta$ W/cm	
			Average		Maximum			
	Average (a)	Max. (b)	W/cm^2	BTU/hr ft^2	W/cm^2	BTU/hr ft^2	Average	Maximum
AHH	256	284	63	201,000	70	223,000	19.3	21.4
AHJ	341	378	85	268,000	94	297,000	25.7	28.5
AHK	410	455	102	322,000	113	357,000	30.9	34.3
AHL	472	524	117	371,000	130	411,000	35.6	39.5
AHM	478	530	118	375,000	131	416,000	36.0	40.0
AHN	461	510	114	362,000	126	401,000	34.8	38.5
AHO	418	464	104	328,000	115	364,000	31.5	35.0

(a) Average readings based on a reactor power of 32 MW and a loop power output of 46 kW after correction for heat loss and γ heating. Moderator height 250 cm.

(b) Maximum readings based on a maximum reactor power of 35.4 MW and a maximum loop power output of 51 kW after correction for heat loss and γ heating. Moderator height 250 cm.

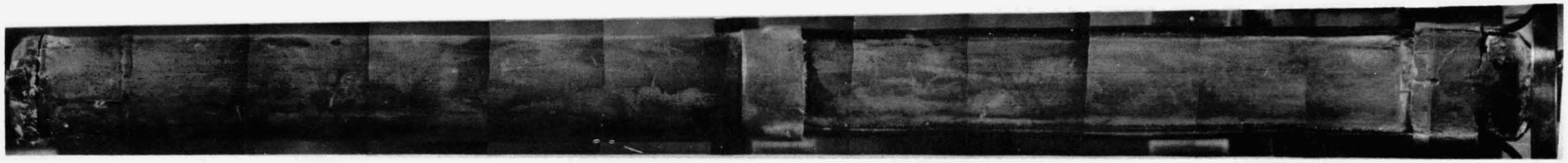

Figure 1 Specimen AHL after irradiation with the surface of the SAP essentially free of organic fouling film. Notice the spider end and middle bands holding the sheath thermocouples.

Magnification 4X Reference Nos. 5406-5418

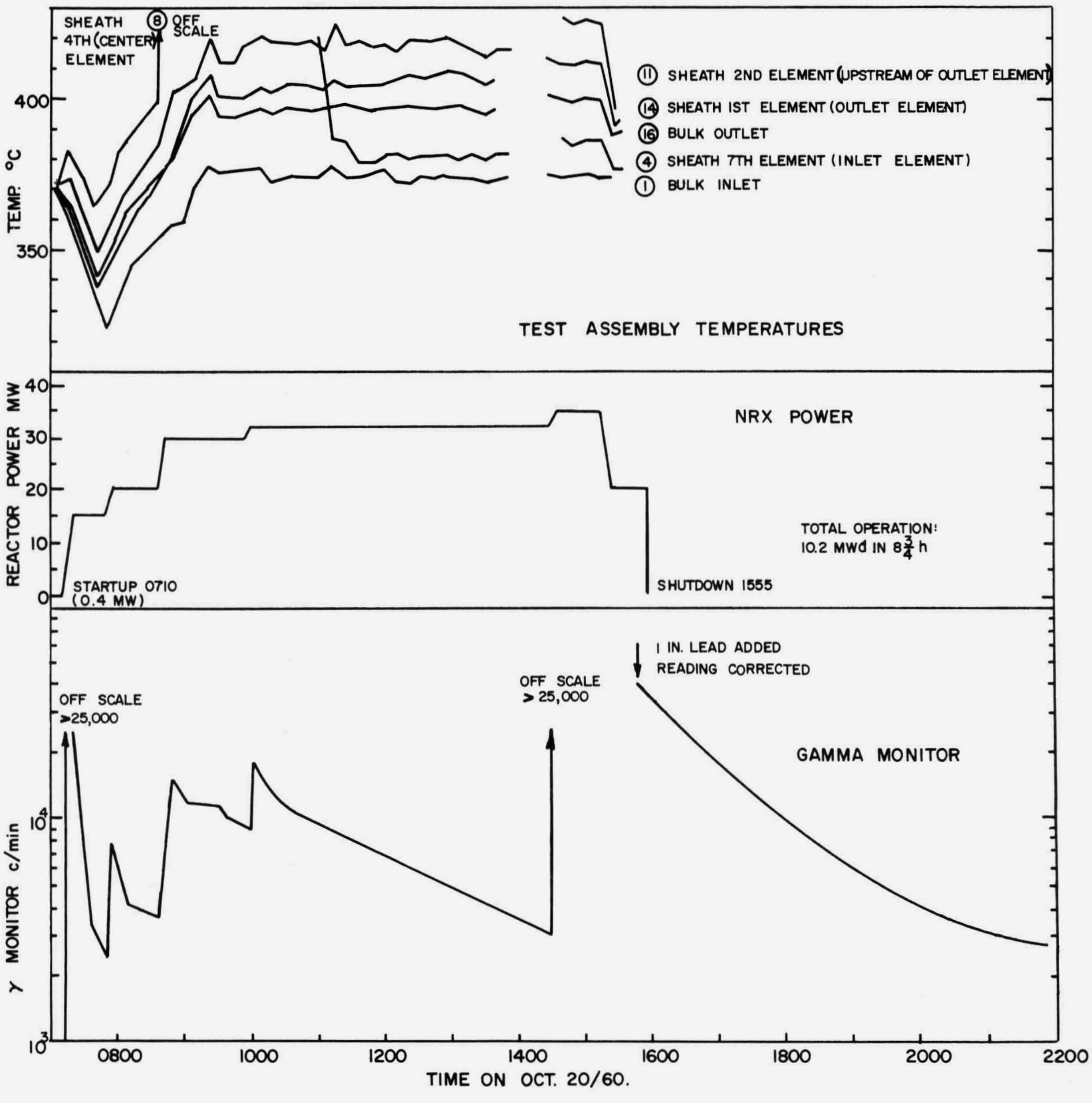

FIGURE 2. OPERATING CONDITIONS DURING X-58 TEST.

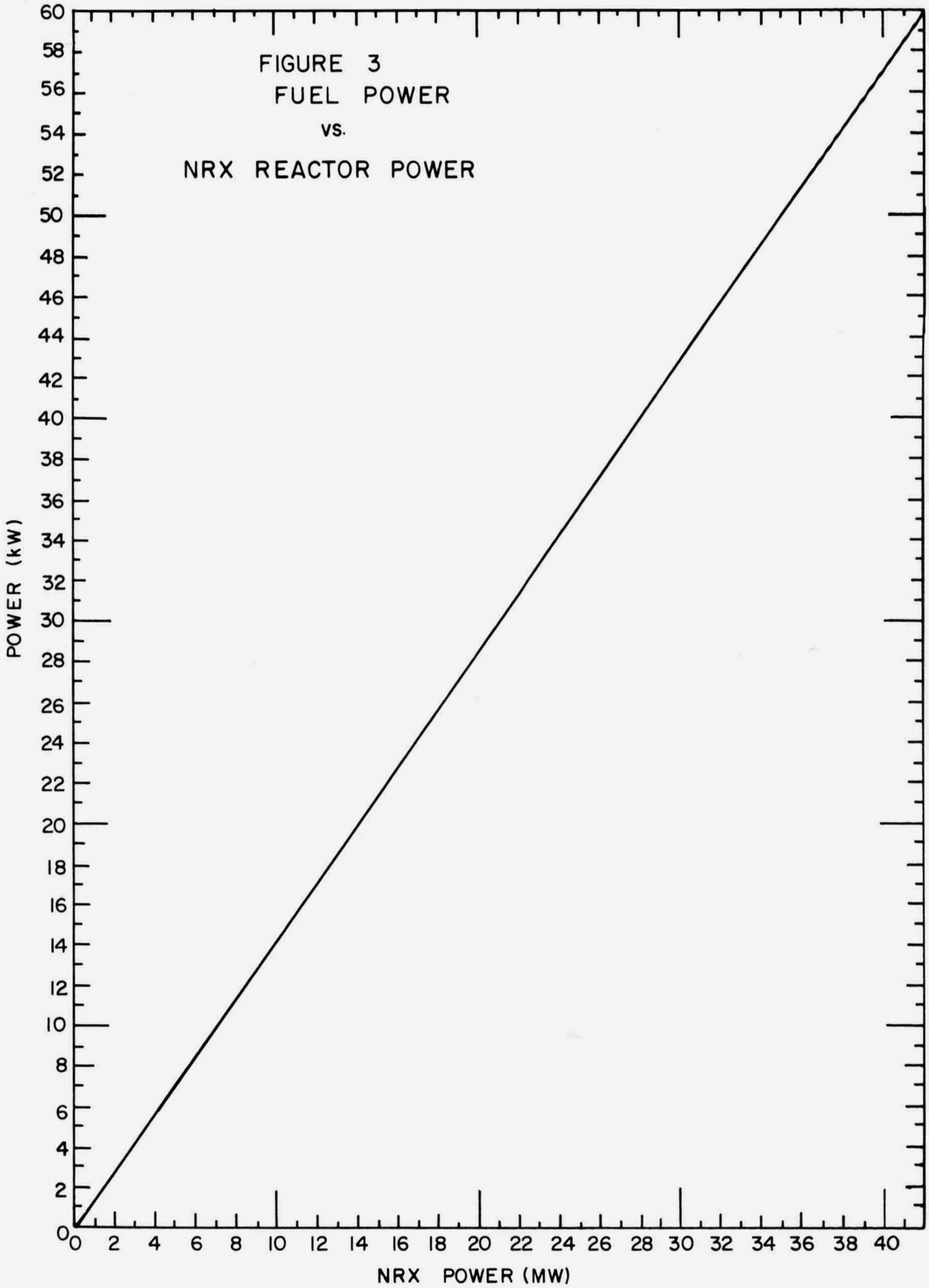
FIGURE 3
FUEL POWER
VS.
NRX REACTOR POWER
POWER (kW)
NRX POWER (MW)
0
2
4
6
8
10
12
14
16
18
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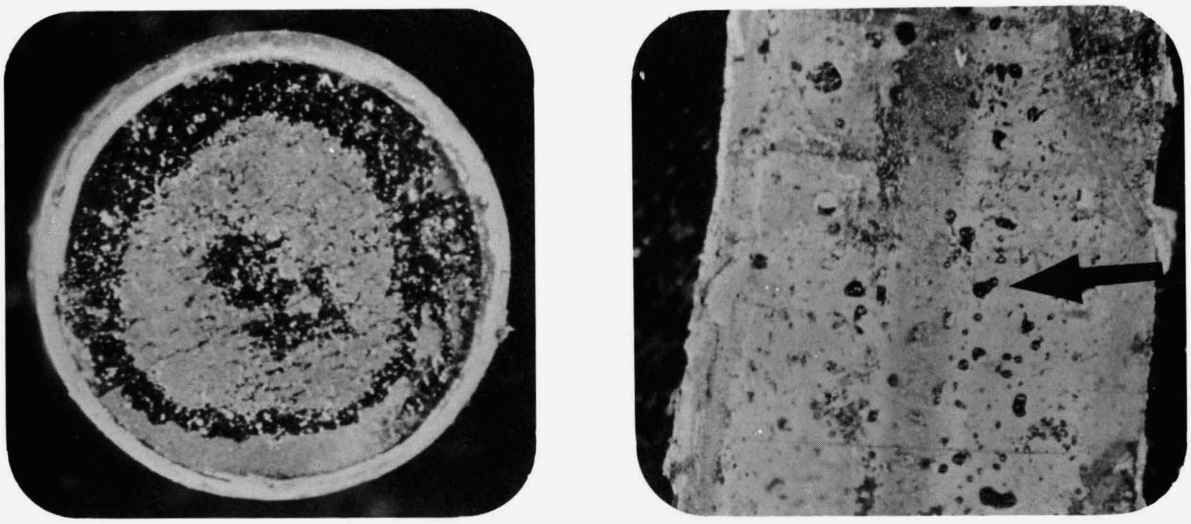

Figure 4 Left: Organic coolant which has penetrated into interface between UO_2 pellets of AHL

Magnification 4 X Reference No. 5469

Right: Droplets of solidified organic coolant (arrow) on the inside surface of AHK sheath.

Magnification 13 X Reference No. 5538

Figure 5 A pellet face from specimen AHL with concentric colouration rings on the surface. Note the porous center of the UO_2 pellet.

Magnifications 4X and 13X References Nos. 5464, 5465

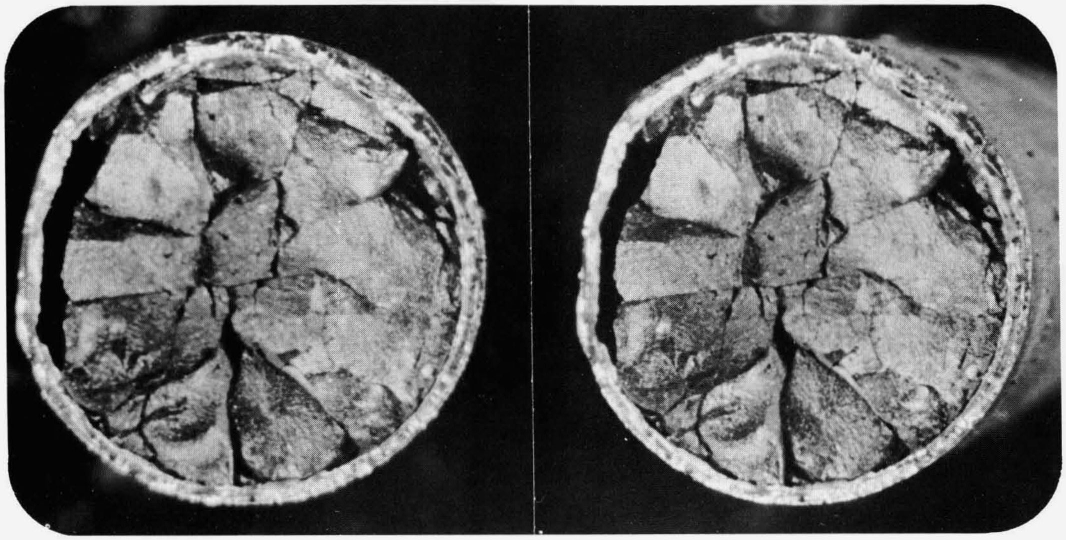

Figure 6 Typical fuel cross-section from element AHN (stereopair)

Magnification 4 X Reference No. 5558

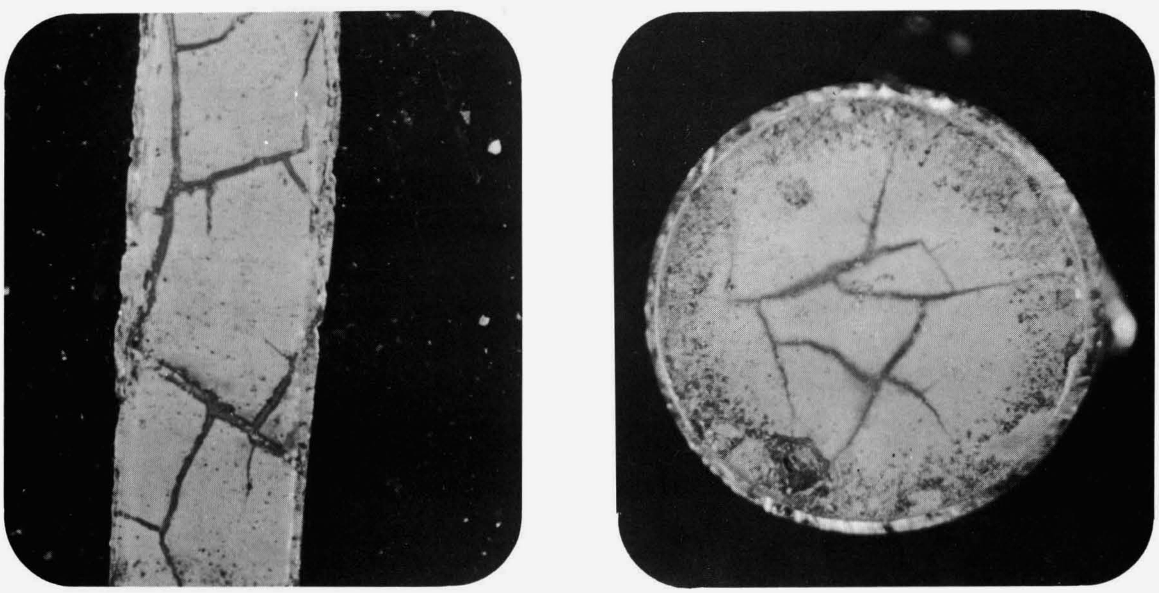

Figure 7 Left: The cracking pattern on the inside surface of the SAP sheath from specimen AHN.

Magnification 4 X Reference No. 5554

Right: Pellet cracking pattern on the inside surface of the lug end cap from the same specimen.

Magnification 4X Reference No. 5557