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AEC RESEARCH AND DEVELOPMENT REPORT

HEAVY WATER MODERATED POWER REACTORS

PROGRESS REPORT
SEPTEMBER-OCTOBER 1964

Technical Division
Wilmington, Delaware

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HEAVY WATER MODERATED POWER REACTORS
PROGRESS REPORT
September–October 1964

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Power Reactor Studies
Wilmington, Delaware

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ABSTRACT

The Heavy Water Components Test Reactor (HWCTR) was operated at 50 MW for about 85% of September and October for fuel irradiation tests. At the end of October, the reactor was shut down for removal of poison tubes from the driver fuel assemblies. The removal of the poison tubes will prolong the reactivity lifetime of the drivers. The neutron flux peaks that occur at fuel gaps when a column of short fuel pieces is irradiated were measured for three types of HWCTR fuel assemblies in an exponential facility. Further examination of a tube of unalloyed uranium irradiated to 6830 MWD/MTU in the HWCTR confirmed earlier indications of severe buckling of the inside surface of the tube.

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HEAVY WATER MODERATED POWER REACTORS
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INTRODUCTION

This report reviews the progress of the Du Pont development program on heavy-water-moderated power reactors. The goal of the program is to advance the technology of these reactors so that they could be used in large power stations to generate electricity at fully competitive costs. Most of the effort is concerned with (1) the irradiation of candidate fuels and other reactor components in the Heavy Water Components Test Reactor (HWCTR), and (2) the development of low-cost fuel tubes for use in large water-cooled reactors.

In September 1964, the Atomic Energy Commission announced that its development of D_2O power reactors is being redirected toward the use of an organic coolant. In view of this decision, the Du Pont program on water-cooled reactors has been curtailed. Operation of the HWCTR is being continued, but no new fuel irradiation specimens are being fabricated. Fuel elements for HWCTR irradiation tests will be drawn from a supply already on hand. The program on uranium metal tubes is being brought to an orderly conclusion, and the development of uranium oxide tubes is being restricted to (1) irradiation and postirradiation examination of existing fuel assemblies, and (2) fabrication of a set of oxide drivers for the HWCTR (DP-905). The Engineering Department cost study of a 1000-MWe D_2O-cooled reactor (DP-925) has been terminated, as have the heat transfer experiments with boiling water at Columbia University.

SUMMARY

The HWCTR was operated at 50 MW for about 85% of September and October for fuel irradiation tests. A shutdown of 6 days duration was required for repair of a D_2O leak in one of the steam generators. This was the fourth such leak since February 1964. At the end of October, the reactor was shut down for removal of boron stainless steel poison tubes from the driver fuel assemblies. It is estimated that when the poison tubes are removed, the driver fuel will have enough nuclear reactivity for an additional 50 full-power days of reactor operation.

The neutron flux peaks that occur at fuel gaps when a column of short fuel pieces is irradiated were measured for three types of HWCTR fuel assemblies in an exponential facility. The results show that neutron absorbers must be inserted between the fuel pieces to avoid

excessive local heat generation at projected irradiation conditions. Tentative selections of suitable absorber materials for columns of uranium oxide tubes and columns of uranium metal tubes were made on the basis of the flux peaking measurements.

Metallographic examination of a U - 2 wt % Zr tube irradiated in 1959 in the Vallecitos Boiling Water Reactor revealed that the observed swelling of the tube during irradiation (3.6% at 1400 MWD/MTU* and 430°C) was caused by the formation of large cavities in the fuel core. Further examination of a tube of unalloyed uranium that survived irradiation to 6830 MWD/MTU in the HWCTR confirmed earlier indications of severe buckling of the inside surface of the tube. The causes of the core swelling that led to the buckling are being investigated in metallographic examinations of the tube.

* Megawatt-days per metric ton of uranium.

DISCUSSION

I. THE HEAVY WATER COMPONENTS TEST REACTOR (HWCTR)

The HWCTR is a D_2O-cooled-and-moderated test reactor in which candidate fuel assemblies and other reactor components are being evaluated under conditions that are representative of large water-cooled D_2O-moderated power reactors. Currently, fuel tubes of uranium oxide (mechanically compacted in Zircaloy sheaths), uranium metal (coextruded in Zircaloy sheaths), and thorium metal (coextruded in Zircaloy sheaths) are being irradiated in this reactor. Operating data are summarized in Tables I and II and in Figures 1 and 2. Irradiation tests currently in progress are summarized in Tables III and IV.

The HWCTR operated at 49-53 MW for about 85% of the time during September and October. A shutdown of six days was required to repair a heavy water leak in the No. 1 steam generator. This leak was the fourth that developed in the steam generators since February 1964 (DP-895, -915, -925). As indicated in DP-925, the condition of the steam generators is ascribed to excessive corrosion resulting from ineffective control of dissolved oxygen in the secondary cooling water. The treatment of the water has been modified to eliminate essentially all oxygen. The reactor was down for one day to repair a heavy water leak in a 3-inch check valve in the liquid-D_2O-cooled loop. This leak was the result of a design deficiency in the valve, and the condition has been corrected. The preliminary data on heavy water losses since this repair indicate that the leak may have been as large as 20 to 25 pounds a day during the two to three months prior to its final detection.

The driver fuel elements (9.3% ^{235}U in Zr) were operated at a maximum metal temperature of 580°C until the maximum burnup reached 1.2 atom %, at which time the temperature was lowered to 560°C. On the basis of results from earlier examinations of the driver elements, the interim examination originally scheduled at a burnup of 1.2 atom % (DP-925) was postponed until a burnup of 1.4 atom % to coincide with a shutdown for removal of poison tubes from the driver assemblies. The reactivity left in the driver elements after the interim examination is complete and the boron - stainless steel poison tubes are removed is estimated to be sufficient for an additional 50 full-power days of operation. The reactor was shut down on October 31 for removal of the poison tubes.

II. REACTOR PHYSICS – NEUTRON FLUX PEAKING AT FUEL GAPS IN HWCTR ASSEMBLIES

Many of the test and driver fuel assemblies scheduled for irradiation in the HWCTR are composed of columns of short fuel tubes. The absence of fuel at each end of these sections gives rise to regions of low neutron absorption, where flux peaking will occur with a resultant possibility of excessive heat generation in the fuel adjacent to the end plugs. A program of test irradiations was undertaken in the Subcritical Experiment (SE) at the Savannah River Laboratory to measure this flux peaking for typical tubular fuel specimens and to determine the effectiveness of various added absorbers in decreasing or eliminating the effect.

All tests were made on single test assemblies at the center of the SE, which is an exponential facility. The driver fuel consisted of enriched uranium fuel tubes at a lattice pitch of 7.00 inches. The flux distributions at the fuel gaps in the test assemblies were determined by activating manganese alloy wires 0.06 inch in diameter and 18 inches long. Three such wires were positioned parallel to the axis of each fuel tube on its clad exterior surface. The wires were scanned by a scintillation counter system with a spatial resolution of 0.25 inch. The results are presented below.

A. SEGMENTED OXIDE TUBE TEST ASSEMBLIES

These fuel pieces consist of vibratorily compacted UO_2 powder in Zircaloy sheaths. A fuel assembly of the following specifications was used for the SE:

Clad dimensions,	OD: 3.665 in.
	ID: 2.990 in.
UO_2 density:	90% of theoretical
Cladding:	Zircaloy, 0.036-in. thick
Enrichment:	1.2 wt % ^{235}U
Over-all length:	24 in., each tube
Core length:	21 in., each tube

The fuel terminations were abrupt. Flux profiles were measured with and without various flux depressing poison rings inserted between the fuel pieces. These rings had the same radial dimensions as the clad fuel and were of the following types:

(1) 0.030-inch-thick cadmium metal (one or three rings)

(2) 0.030-inch-thick gadolinium metal

(3) 0.50-inch-thick stainless steel

(4) 0.50-inch-thick silver-indium-cadmium alloy

The measured flux profiles are shown in Figure 3. The cadmium, gadolinium, and silver-indium-cadmium absorbers completely eliminated the flux peaking. The stainless steel rings left a residual 3% peak at the end of the fuel, but were chosen for HWCTR irradiations because these rings can be inserted directly into the HWCTR without special cladding.

B. ENRICHED URANIUM METAL TUBES

These fuel pieces consist of uranium metal tubes coextruded with a Zircaloy cladding. Tubes of three different ^{235}U concentrations were used as a source of samples for the SE tests. Two 24-inch-long samples were cut from the ends of each of these tubes. The result was an abrupt fuel ending at the location of the cut and a tapered ending at the other end of the 24-inch section. The taper was a result of the coextrusion method of fabrication. The specifications for the three tubes were as follows:

Tube	^{235}U	Core, inches		Length of Core Taper, inches		Distance from End of Tube to End of Tapered Core, inches	
No.	Enrichment	OD	ID	Front[a]	Rear[a]	Front[a]	Rear[a]
8	Natural	2.010	1.745	15 to 16	8 to 9	2.1	2.0
115	3 wt %	2.010	1.750	16	5.4	2.8	2.8
146	2.1 wt %	0.975	0.705	12 to 14	12 to 14	2.1	2.1

(a) Front and rear refer to the extremities of the original tubes before they were cut.

Flux ratios were obtained for these tubes under two conditions: (1) with the abrupt ends (full cores) facing each other, and (2) with the tapered ends facing each other to form the gap. Various spacings were obtained by the addition of aluminum spacer rings between the tubes. The measured maximum flux values at the midpoint of the gap, relative to that in the continuous part of the fuel, are shown in Figure 4 for two fuel enrichments. Contrary to expectations, the flux peaking in the gaps between the tapered ends was less than that between the full core ends. The resolution of this discrepancy was obtained when X-radiographs of the fuel elements showed that the fuel tapers were more than 12 inches long. As a result, the flux characteristic of the uniform tube was not obtained with the 18-inch-long test wires.

Poison rings of 0.030-inch-thick and 0.060-inch-thick cadmium were inserted into fuel gaps of various thicknesses. However, for the anticipated fuel separations under HWCTR irradiation conditions, these poison rings were insufficient to hold flux peaking to satisfactory bounds. Special sleeves of a more strongly absorbent cobalt-base alloy (51% Co, 20% Cr, 15% W, 10% Ni) are being fabricated to provide adequate flux suppression.

C. DRIVER FUEL ASSEMBLIES OF ENRICHED URANIUM OXIDE

These fuel pieces consist of vibratorily compacted enriched UO_2 in Zircaloy sheaths. Each assembly comprises two nested tubes. The specifications for the driver assemblies in the SE measurements are shown below:

Tube No.	^{235}U Enrichment, wt %	% of Theoretical UO_2 Density	Core Dimensions, inches OD	ID	Thickness
0-4	4.5	80.5	2.705	2.343	0.181
0-5	4.5	76.1	2.204	2.341	0.181
I-1	4.5	78.1	1.486[a]	1.086[a]	0.200[a]
I-5	4.5	78.5	1.486[a]	1.086[a]	0.200[a]

Over-all length = 15 in., Core length = 14 in.

(a) ±0.002

In the HWCTR only the inner of the two nested fuel tubes will be segmented. Flux peaking measurements for these assemblies were thus made at gaps in the inner fuel only; i.e., the outer fuel tube was continuous. With no added absorber, the maximum value of the flux peaking was 20%, with values of 11% at the ends of the fuel. The flux peaking was also measured with 0.030- and 0.060-inch-thick cadmium rings inserted in the gap. These poison rings were not sufficiently strong to reduce the flux to suitable levels. Accordingly, additional measurements were made with poison added in the form of a sleeve of stainless steel containing 1.2 wt % boron. The sleeve was 0.010 inch thick and just long enough to cover the fuel gap. This absorber was capable of eliminating the flux peak. For the actual HWCTR assemblies, suitably strong absorbers will be added in the form of sleeves of the same cobalt-base alloy to be used for the uranium metal tubes.

III. POSTIRRADIATION EXAMINATIONS OF FUEL TUBES

A. URANIUM - 2 wt % ZIRCONIUM

Metallographic examination of a U - 2 wt % Zr tube irradiated in 1959 in the Vallecitos Boiling Water Reactor (VBWR) demonstrated that, in spite of the reactor coolant pressure of 1000 psi, large cavities formed that caused the tube to swell during irradiation. The tube, manufactured by coextrusion with a Zircaloy-2 cladding, was irradiated to 1280 to 1400 MWD/MTU at a maximum metal temperature of 430°C.[1] During irradiation, the tube swelled as much as 3.6%, as indicated by dimensional measurements; most of the swelling occurred after a threshold exposure of about 1000 MWD/MTU. The tube was examined metallographically to establish the effects of elevated surface temperatures and reactor pressure for comparison with similar tubes irradiated at low surface temperatures and pressures in Savannah River reactors.

Cavities were observed in sections of the tube that operated at uranium temperatures of 400 to 430°C and to exposures of 1150 to 1400 MWD/MTU. The cavities were similar in appearance to those observed in unalloyed uranium and U - 2 wt % Zr irradiated in Savannah River reactors. The swelling due to cavitation, as determined by point-count techniques, was essentially constant (about 3.3 to 3.6 vol %) over the stated range of irradiation conditions. These results agreed with volume changes of 3.5 to 4.2%, as estimated from dimensional measurements of the corresponding tube section at Savannah River, but were greater than the volume changes of 1.3 to 3.6% calculated from VBWR measurements. Although cavity volumes measured by point-count techniques may be slightly high, it appears certain that external pressurization to 1000 psi during irradiation did not prevent the formation and growth of cavities.

Oriented zirconium hydrides were observed in the outer and inner cladding. The concentration, 3 to 9 vol %, was too low and the distribution too uniform to lead to brittle failure of the cladding. Hydrides were predominantly perpendicular to the surface in outer cladding and parallel to the surface in inner cladding.

B. UNALLOYED URANIUM

As reported in DP-895, two thin-walled fuel tubes with unalloyed uranium cores and Zircaloy cladding survived irradiation in the HWCTR to 6830 and 6470 MWD/MTU at time-averaged uranium temperatures of 500 and 515°C, respectively. Dimensional measurements showed that the 2-in.-OD tubes, each housed in a four-ribbed Zircaloy outer housing and a four-ribbed stainless steel inner housing, underwent outside diameter changes ranging between about -0.050 and +0.050 in. in the highest-temperature sections; diameter increases occurred at the ribs of the inner housing and diameter decreases occurred between the ribs. The inner housings, with 0.030-in. diametral clearance prior to irradiation, were stuck firmly inside the tubes, indicating substantial decreases in the inner diameter of the tubes.

Disassembly of one of the tubes and examination of its cross section have confirmed severe buckling of the inside surface in a pattern conforming to the inner housing rib configuration. As shown in Figure 5, buckled regions formed longitudinal ridges as much as 0.1 inch high between the inner housing ribs. The inside diameter of the tube was so irregular that precise dimensional measurements could not be obtained. The densities of selected specimens will be measured to determine the volume increase that occurred during irradiation.

The cut surfaces of the tube segments did not show any gross cavities or core cracks. More detailed metallographic examinations will be made to determine the nature of the internal porosity that produced swelling of the tubes.

C. HWCTR DRIVER TUBES

The driver tubes in the HWCTR are an alloy of Zr - 9.3 wt % U, enriched to 93% ^{235}U and clad with 0.015 inch of Zircaloy. They are irradiated in the as-extruded condition. During the first driver cycle of the HWCTR, the drivers operated at central metal temperatures of 500°C (average) and a pressure of 1000-1200 psi. Burnup reached 1.9 atom %.

Dimensions of two drivers that were operated at the highest flux during the first cycle were measured during the course of irradiation to record the progress of swelling. In both instances, the observed swelling followed approximately the curve predicted on the basis of the accumulation of solid fission products. Postirradiation metallographic examination has confirmed that there was very little fission gas swelling and no cavitation swelling. Figure 6 shows the microstructure before and after irradiation. The only observable changes in the microstructure were spheroidization of the epsilon phase and precipitation of a few scattered fission gas bubbles. No hydride was observed in the cladding of the tubes.

TABLE I

Operating Chronology of HWCTR

Sept. 1-9	Operated at 49 MW
9	Shut down - steam generator leak
9-15	Repaired steam generator leak
15	Attained criticality and 43.5 MW
16	Attained 48 MW
16-20	Operated at 48 MW
20	Attained 50 MW
20-27	Operated at 50 MW
27	Attained 52 MW
27-30	Operated at 52 MW
30	Attained 53 MW
30	Shut down - high level flux monitor scram during electrical storm
Sept. 30 - Oct. 1	Held down by xenon
1	Attained criticality and 21 MW
2	Attained 50 MW
2-4	Operated at 50 MW
4	Attained 51 MW
4-7	Operated at 51 MW
7	Shut down - investigate D_2O leak in building
7-8	Repair leak in 3-inch check valve
8	Attained criticality and 18 MW
9	Attained 49 MW
10	Attained 50 MW
10-12	Operated at 50 MW
12	Shut down - scram from work on unbypassed instrument
13	Attained criticality
13	Shut down - scram - bypassed three High Level Flux Monitors
13	Attained criticality and 30 MW
14	Shut down - scram from work on unbypassed instrument
14	Attained criticality and 49 MW
15	Attained 50 MW
15-22	Operated at 50 MW
22	Attained 51 MW
22-26	Operated at 51 MW
26	Attained 53 MW
26-28	Operated at 53 MW
28	Attained 54 MW
28-31	Operated at 54 MW
31	Shut down for scheduled inspection of driver fuel and target replacement

TABLE II

Operating Summary of HWCTR

	September		October	
Time reactor critical, %	80.1		83.1	
Maximum power, MW	53		54	
Reactor exposure, MWD	Drivers	Test	Drivers	Test
For month	946	223	1038	243
Accumulated in H-2 cycle	3363	657	4401	900
Losses				
D_2O (100 mole %), lb[a]	1220		782	
% of inventory per year	20.9		13.4	
Deuterium, g	3479		4094	
Helium, scf	63,600		51,938	

(a) Loss through defective steam generator tubing has averaged about 15 lb/day (7.85% of inventory per year) during this period and is included in these numbers (ref. DP-925).

TABLE III

Test Fuel Irradiation Data
October 1964[a]

Reactor power	53 MW
Coolant pressure	1200 psig
Moderator outlet temperature	200°C
Coolant inlet temperature	181°C

		Maximum Nominal Conditions								Maximum Exposure[d], watt-days/g	
Position	Element Number[b]	Assembly Power[c], MW	Specific Power[d], watts/g	Heat Flux, pcu/(hr)(ft²)	Outlet Temp., °C	Surface Temp., °C	Core-Clad Temp., °C	Core Temp., °C	∫kdθ, watts/cm	Attained	Planned
37	TMT-1-3	1.23	53.0	408,000	212	248	374	477	-	2,840	20,000
38	SOT-6-2	0.66	45.5	257,000	246	272	333	-	28.0	4,590	30,000
39	SOT-8-2	1.09	61.5	301,000	198	233	332	-	28.7	3,280	30,000
40	TMT-1-2	1.26	54.5	419,000	212	250	379	484	-	2,920	20,000
42	SOT-8-3	1.17	66.5	323,000	199	235	341	-	30.8	3,580	30,000
55	SOT-6-3	0.67	45.5	257,000	230	284	345	-	28.0	2,860	30,000
56	SOT-1-4	0.58	63.5	283,000	190	233	315	-	22.5	11,260	30,000
57	OT-1-7	0.72	57.5	267,000	193	233	313	-	21.2	9,830	30,000
58	SOT-1-2	0.50	53.0	238,000	189	223	292	-	18.8	16,940	30,000
59	SOT-9-2	0.92	61.5	348,000	231	285	368	-	37.7	3,330	20,000
60	OT-1-4	0.85	66.5	309,000	195	238	331	-	24.5	10,580	30,000

(a) Data taken on 10/27/64; exposures as of 10/31/64. Reactor power 53 MW.
(b) Elements are identified in Table IV.
(c) "Flow-ΔT" power calculations; does not include moderator heating.
(d) These values are based on an assembly power of 1.09 times "Flow-ΔT" power to include moderator heating.

TABLE IV

Fuel Identification Data

Designation	Shape	OD, in.	ID, in.	Unit Length, in.	Units	Description
SOT-1	Tube	2.06	1.47	14	7	1.5% enriched UO_2 vibrated and swaged in Zircaloy
OT-1	Tube	2.06	1.47	120	1	Same as SOT-1
SOT-6	Tube	2.54	1.83	14	7	Natural UO_2 vibrated and swaged in Zircaloy
SOT-8	Tube	3.67	2.99	14	7	1.2% enriched UO_2 vibrated and swaged in Zircaloy
SOT-9	Tube	2.54	1.83	14	7	1.2% enriched UO_2 vibrated and swaged in Zircaloy
TMT-1	Tube	2.55	1.85	120	1	1.4% ^{235}U in thorium metal - Zircaloy clad

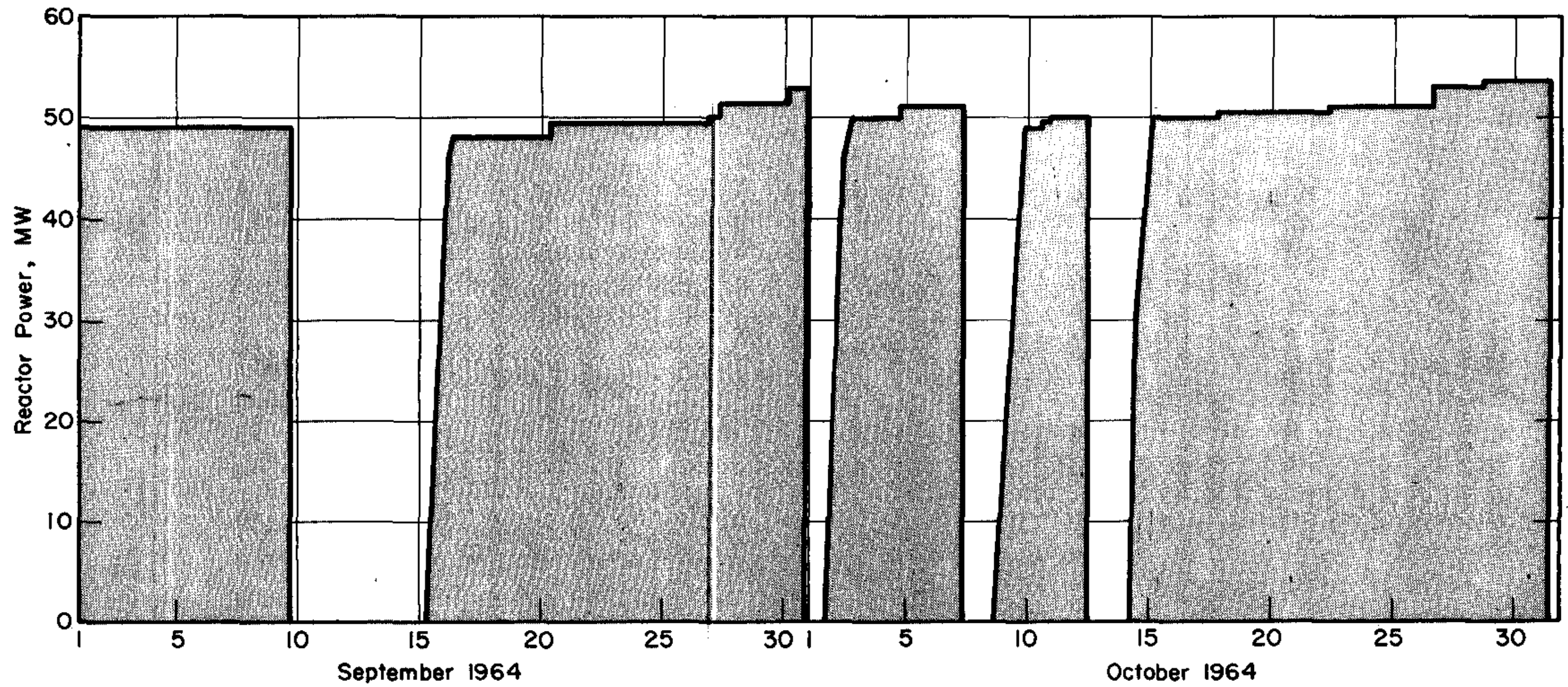


FIG. 1 OPERATING POWER OF HWCTR

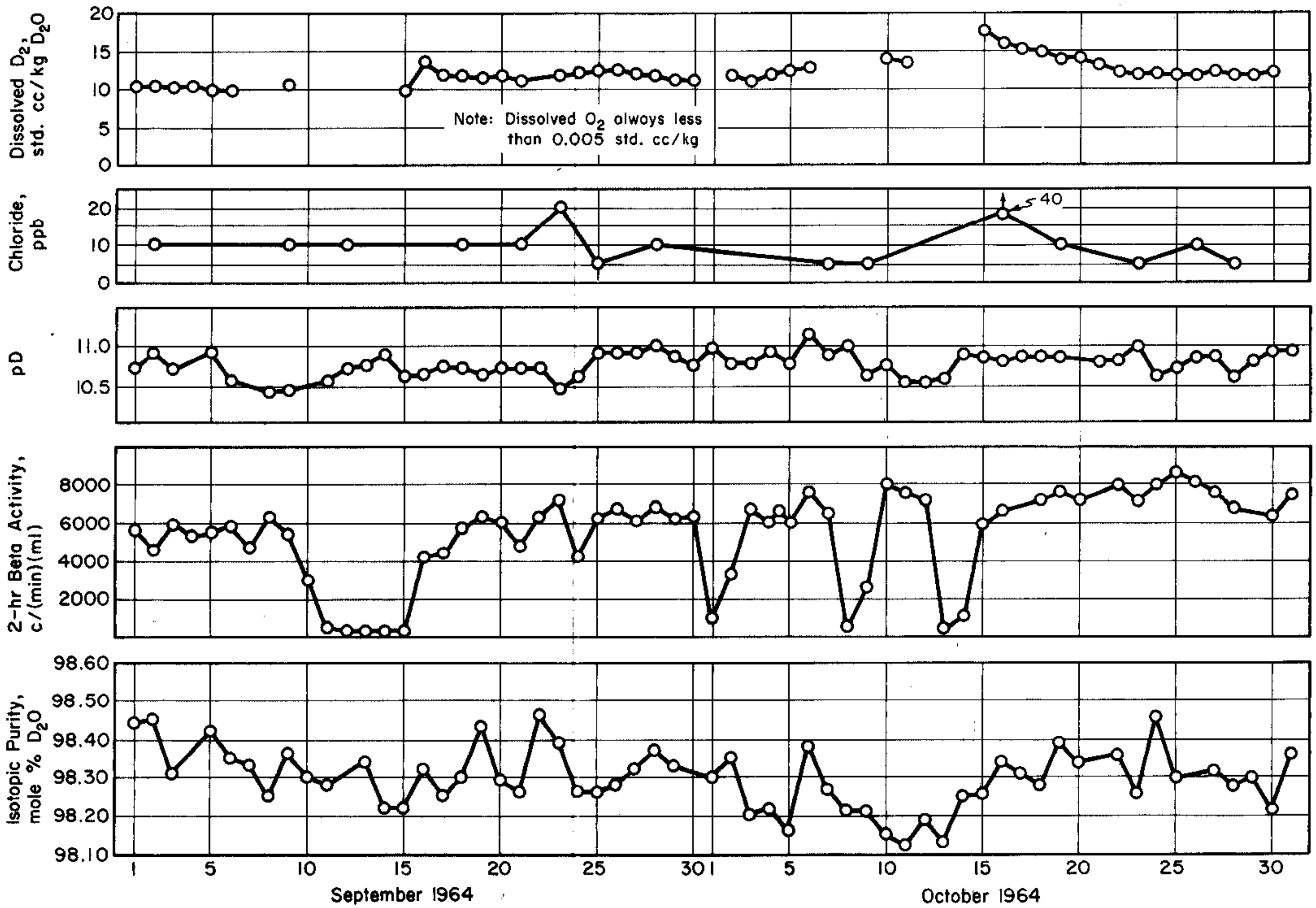


FIG. 2 HEAVY WATER QUALITY IN HWCTR

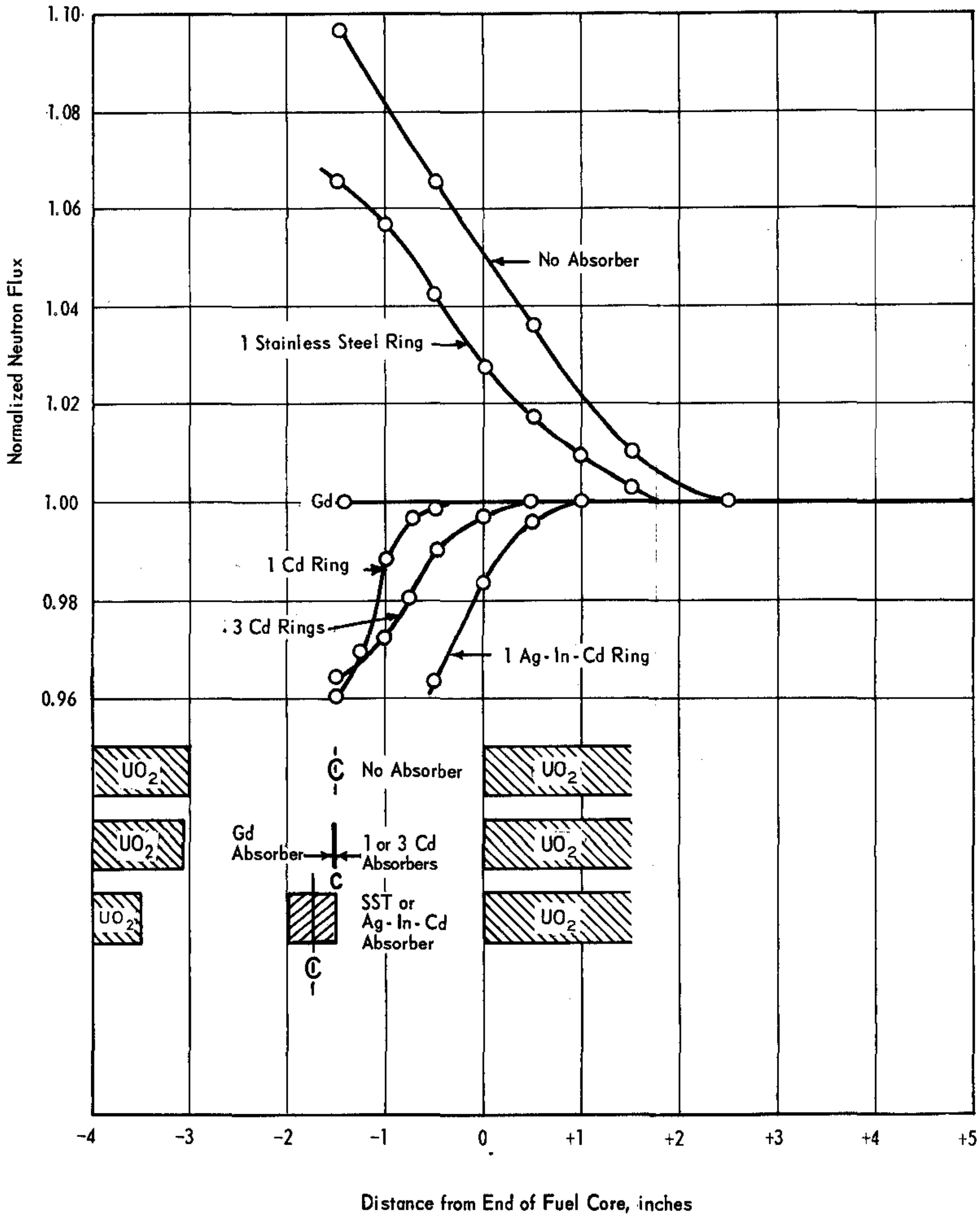


FIG. 3 FLUX PEAKING AT ENDS OF URANIUM OXIDE TUBES

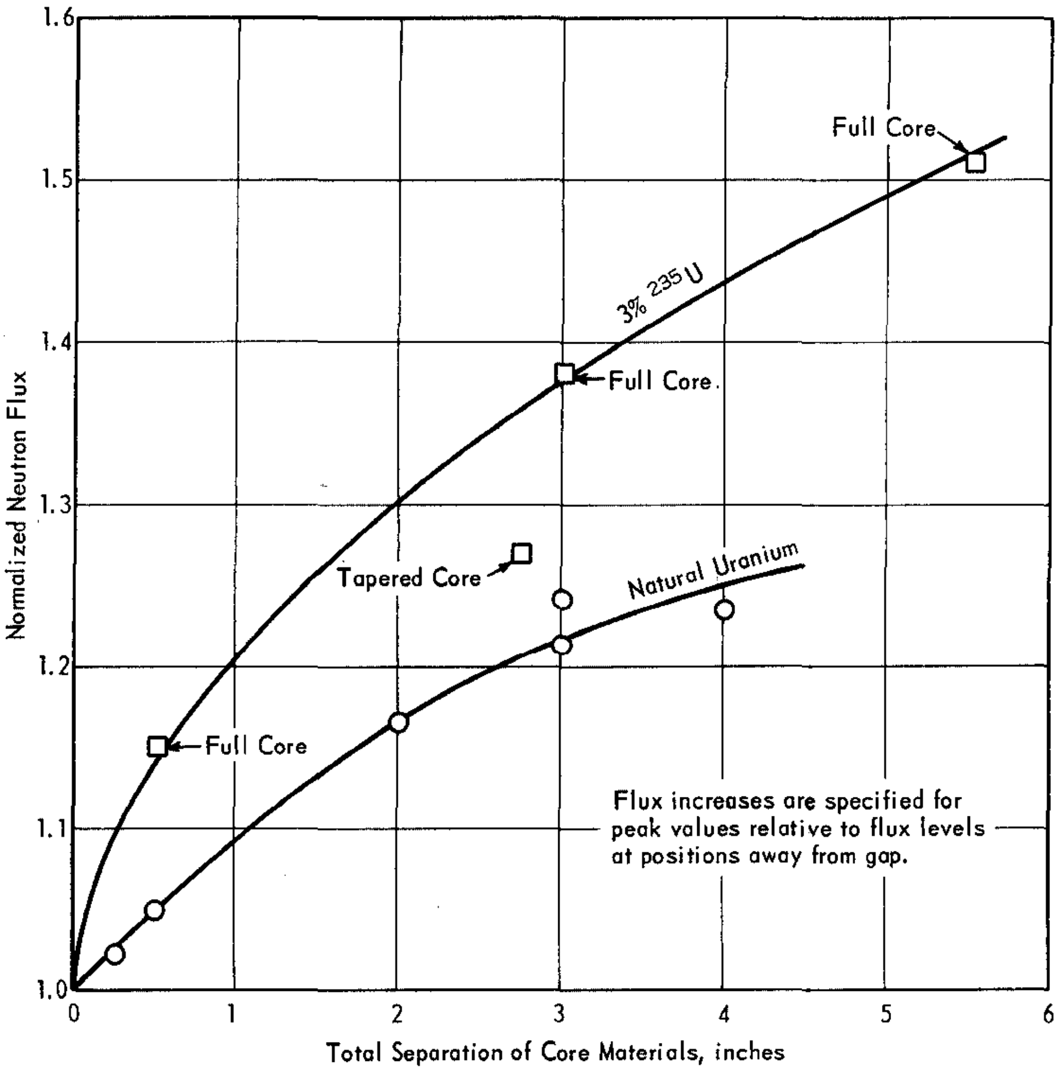
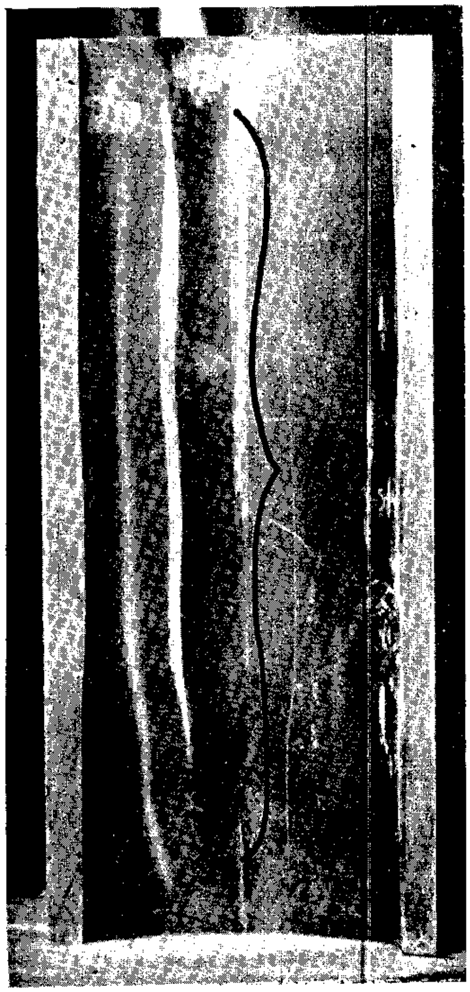
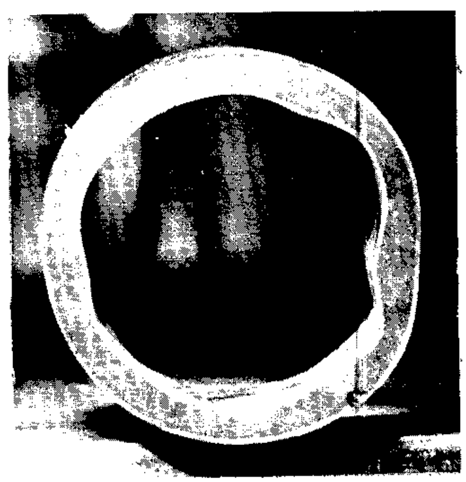


FIG. 4 FLUX PEAKING AT ENDS OF FUEL TUBES OF URANIUM METAL



a. Longitudinal section showing ridge (A) along inner surface of tube

NEG. 62501 1X



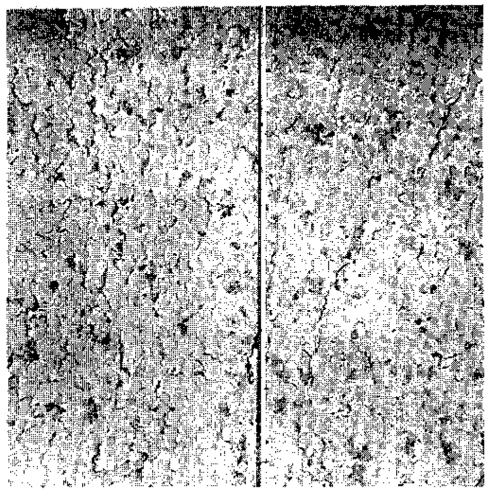
b. Transverse section No gross porosity visible

NEG. 62508 1X

FIG.5 SECTIONS OF UNALLOYED URANIUM TUBE AFTER IRRADIATION TO 6830 MWD/MTU
Zircaloy-Clad Tube from Assembly No. ETWO-2

NEG. 1756 H 6000 X

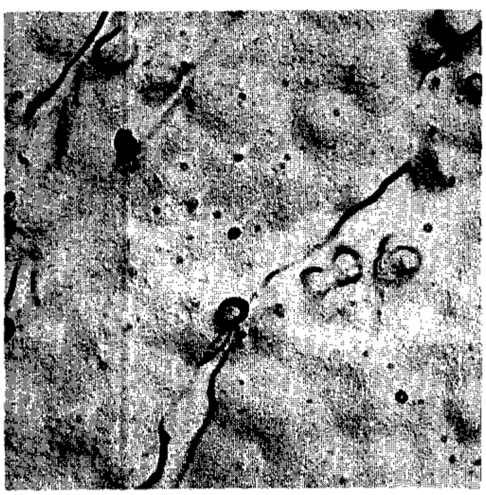
a. Before irradiation .



NEG. 1925 E 6000 X

b. After irradiation (1.9 atom % burnup, 500°C).

Epsilon Phase Distribution



NEG. 1942E 34,000 X

c. Fission gas bubbles after irradiation.

FIG.6 MICROSTRUCTURE OF Zr - 9.3 wt % URANIUM DRIVER TUBES BEFORE AND AFTER IRRADIATION

BIBLIOGRAPHY

1. H. C. Quigley. Irradiation of a U - 2 wt % Zr Fuel Tube in the VBWR. USAEC Report DP-709, E. I. du Pont de Nemours & Co., Savannah River Laboratory, Aiken, S. C. (1962).

2. Previous progress reports in this series are:

DP-232	DP-395	DP-485	DP-575	DP-665	DP-755	DP-845
DP-245	DP-405	DP-495	DP-585	DP-675	DP-765	DP-855
DP-265	DP-415	DP-505	DP-595	DP-685	DP-775	DP-865
DP-285	DP-425	DP-515	DP-605	DP-695	DP-785	DP-875
DP-295	DP-435	DP-525	DP-615	DP-705	DP-795	DP-885
DP-315	DP-445	DP-535	DP-625	DP-715	DP-805	DP-895
DP-345	DP-455	DP-545	DP-635	DP-725	DP-815	DP-905
DP-375	DP-465	DP-555	DP-645	DP-735	DP-825	DP-915
DP-385	DP-475	DP-565	DP-655	DP-745	DP-835	DP-925