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THORIUM-1.4 wt% ^{235}URANIUM METAL FUEL TUBES - FABRICATION AND IRRADIATION IN HWCTR

Edited by S. R. Nemeth

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THORIUM-1.4 WT % ^{235}URANIUM METAL FUEL TUBES - FABRICATION AND IRRADIATION IN HWCTR

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ABSTRACT

Three thorium-1.4 wt % ^{235}uranium alloy fuel tubes with Zircaloy-2 cladding were fabricated. Two of the tubes were irradiated in HWCTR to an exposure of 3500 MWD/Te without failure.

This report describes the joint effort between Nuclear Metals and the Savannah River Laboratory in the development of a coextrusion process for fabrication of these tubes, and includes the results of the irradiation of the tubes in the HWCTR.

CONTENTS

	Page
List of Tables and Figures	iv
Introduction	1
Summary	2
Discussion	2
I. Fabrication	
A. Casting of Billet Cores	3
B. Billet Development and Fabrication	5
C. Tube Extrusion and Evaluation	8
II. Irradiation	
A. Flow Test	10
B. HWCTR Irradiation Results	11
C. Postirradiation Inspection	12

LIST OF TABLES AND FIGURES

Table		Page
I	Extrusion Constants for Th-U and Zircaloy-2	12
II	Hot Hardness of Th-U and Zircaloy-2	13
III	Chemical Analyses for Enriched Castings	13
IV	Description of Enriched Billet Cores	14
V	Extrusion Data for Group of Enriched Th-U Tubes . .	15
VI	Summary of Dimensional Characteristics of Prototype and Enriched Tubes	16
VII	Time-Weighted Average Values for Th-^{235}U Assembly No. TMT 1-2	17
VIII	Variables Versus Specific Exposure for Hottest Region of Th-^{235}U Assembly No. TMT 1-2	18
IX	Time-Weighted Average Values for Th-^{235}U Assembly No. TMT 1-3	19
X	Variables Versus Specific Exposure for Hottest Region of Th-^{235}U Assembly No. TMT 1-3	20

Figure		
1	Bottom-Pour Vacuum Induction Melting Furnace . . .	21
2	Composite Billet Assembly for Th-U Tubular Elements	22
3	Fuel Exposure Intervals in HWCTR	23
4	HWCTR Power Levels During Irradiations of Th-^{235}U Fuel Assemblies	24
5	Pre- and Postirradiation Measurements of Th-^{235}U Tube No. 2.1 (Assembly TMT 1-2)	25
6	Thorium Metal Tube	26

THORIUM - 1.4 WT % ^{235}URANIUM METAL FUEL TUBES - FABRICATION AND IRRADIATION IN HWCTR

INTRODUCTION

The Du Pont program on power reactor development included the assessment of the heavy-water-moderated and -cooled breeder reactor concept operating on the Th-^{233}U fuel cycle. Fabrication of several Th-^{235}U alloy fuel elements was undertaken as a first step in the evaluation of a simulated fuel alloy. Thorium metal was preferred to thorium oxide for this purpose because -

a) metal offers a higher potential breeding ratio,
b) metal of suitable quality was on hand,
c) some thorium fabrication experience had already been obtained, and
d) coextrusion techniques developed in the Du Pont power reactor program for uranium metal fuel could be applied to the thorium case.

The coextruded test elements, having the following dimensions, were designed for a series of irradiations in the Heavy Water Components Test Reactor (HWCTR). See Figure 6, page 26.

Outside diameter, in.	2.540
Inside diameter, in.	1.830
Core thickness, in.	0.290
Cladding thickness, in.	0.030
Overall length, in.	118.0
Core length, in.	108.0

Nuclear Metals (NM) developed and fabricated the copper-jacketed, Zircaloy-2 clad billets of cast Th-1.4 wt % ^{235}U alloy. The extrusion billets were tailored to fit an extrusion press at Savannah River Plant (SRP). Savannah River Laboratory (SRL) extruded the billets and evaluated the prototype elements. Two elements were irradiated in the HWCTR.

This report describes the essential development work and fabrication of two pile-worthy Zircaloy-2 clad Th-^{235}U fuel elements for the HWCTR from July 1963 through August 1964. Results of the irradiation in HWCTR from August 1964 through December 1964 are also reported.

Additional details of the fabrication procedure and the operating history in the HWCTR are given in DP-943, Supplement.

SUMMARY

Core casting techniques and billet designs were developed for the preparation of Th-1.4 wt % ^{235}U coextruded tubular fuel elements. Four billets containing thorium alloyed with natural uranium and three billets containing thorium alloyed with enriched uranium were fabricated at NM and subsequently extruded at SRL.

Coextrusion conditions were determined at NM by small-scale rod extrusions supplemented by hot-hardness measurements of the billet component materials. Two core endshapes were evaluated in prototype billets; the one which provided the shorter end taper was adopted for the enriched billets.

Two extrusion campaigns were conducted at SRL; in the first, one copper, one Zircaloy-2, and three prototype Th-U (natural) tubes were extruded. Of these, the Zircaloy-2 tube and one of the Th-U prototype tubes were used for simulated reactor coolant flow tests; the remaining two prototype tubes were destructively evaluated. Based on the success of this first campaign, a fourth Th-U (natural) and three Th-^{235}U alloy billets were extruded. Two Th-^{235}U fuel elements suitable for test irradiation in the HWCTR were produced. These were irradiated in HWCTR to an exposure of 3500 MWD/Te with satisfactory performance.

DISCUSSION

In connection with studies of D_2O-moderated-and-cooled thorium breeder reactors, a program was undertaken to deliver to HWCTR, two pile-worthy Zircaloy-clad tubular elements of a Th-1.4 wt % ^{235}U alloy. Melting and casting development of Th-U alloys leading to a satisfactory billet design was done at NM. This was followed by extrusion and evaluation of the prototype Th-U tubes at SRL which led to extrusion of the Th-^{235}U subsequently used for irradiation tests in the HWCTR.

Following preirradiation inspection, the two Th-^{235}U fuel elements were irradiated in the HWCTR under a test permit. Results of this irradiation are presented in section II of this report.

I. FABRICATION

A. Casting of Billet Cores

1. Equipment, Materials, and Methods for Casting Th-U Alloys

The melting and casting of thorium base alloys containing small amounts of U presents a number of problems, most of which are the result of the high melting point and chemical reactivity of thorium. The induction-melting procedure used in this work relied on coated graphite crucibles with bottom-pouring into graphite molds designed for rapid upward directional solidification.

a. Melting Furnace

The equipment for melting (see Fig. 1) consisted of a 100-KW, 3000-cycle, water-cooled, vacuum-induction furnace of the quartz-tube, bottom-pour type. The quartz tube had an inner diameter of 13 inches. One advantage of the tube-type furnace for thorium melting is that the high level of radioactivity of the volatile decay products is restricted to a limited, accessible area of the furnace. The normal tilt-pour, tank-type furnace involves a substantial interior surface area, which is much more difficult to decontaminate.

b. Crucibles and Molds

Selection of Crucible Material. Coated graphite crucibles were selected for the melting of thorium. Ceramic crucibles (BeO, ThO_2, and ZrO_2) were considered in order to avoid the problem of carbon pickup encountered in melting in graphite. Beryllia, in particular, exhibits low attack by thorium and has good resistance to thermal shock. For ceramic crucibles of the size necessary for this work, however, the high first cost and problems in bottom-pouring from refractory crucibles could not be justified when compared to coated graphite.

c. Charge Materials

Unalloyed thorium was supplied for this program in several shapes, as follows.

- Vacuum-melted ingot hot tops from Davison Chemical Co. These pieces (mostly about 8-1/4 inches diameter and 2- to 6-inches long) could be identified and individual carbon analyses were known.

- Fuel slugs, 1 to 1-1/4 inches diameter and 6-inches long from National Lead Company of Ohio (individual carbon analyses not known but inferred from analyses of similar material).

- Extruded rod ends approximately 3 inches diameter X 6 to 24-inches long from storage at SRP (individual carbon analyses were not known but were inferred from analyses of similar material).

The natural uranium and oralloy (93% ^{235}U) were in the form of 1-inch diameter short-length cylinders

d. Heating Schedule

In the melting of these alloys it is desirable to use rapid heating with a minimum holding time and temperature of superheat to minimize the solution of carbon in the melt. A typical heating schedule for a 200-pound melt of Th-1.61 wt % U alloy is as follows.

Time, minutes	Input Power, kw	Vacuum, microns	Melt Temperature, °C	Remarks
0	65	3	-	-
20	65	20	-	Uranium is liquid in cavity in Th piece.
28	65	80	-	Liquid Th-U alloy covers bottom of crucible.
37	65	50	1675	Molten pool.
40	65	150	1700	-
42	45	200	1725	-
45	45	250	1750	Poured melt.
45	Off		1750	-

Temperatures were measured by means of an optical pyrometer. A nominal pouring temperature of 1750 °C was used, or about 75°C above the observed liquidus of the alloy. This temperature was high enough to provide good fluidity of the metal when cast, and yet was low enough to minimize the time to reach pouring temperature.

B. Billet Development and Fabrication

1. Determination of Deformation Resistance

Knowledge of the deformation resistance of the Th-U core alloy at elevated temperatures was needed to aid the design of core preshapes and the selection of an optimum temperature for coextrusion with Zircaloy. Extrusion constants for Th-1.5 wt % U alloy were determined by rod extrusions in which temperature and carbon content were studied as variables. This was supplemented by hot-hardness tests over a wider temperature range.

a. Extrusion Constants

Three rods were extruded under the conditions given in Table I. Two of the extrusions were made with composite billets (1404-1 and 1404-2) consisting of cylinders 1.85-inches in diameter X 1-1/2-inches long, assembled end-to-end in the order of (1) copper, (2) Zircaloy-2, (3) Th-U alloy, (4) Zircaloy-2, (5) copper, and sealed within an evacuated copper can 2-inches OD X 1.870-inches ID. The third billet (1429) was similar except that it had two cylinders of Th-U of differing carbon content interposed between the Zircaloy-2 cylinders. The Th-U was machined from hot tops produced in the casting development phase of this program. Nickel-free Zircaloy-2 was used in the billets because it was available in a suitable size and had previously appeared indistinguishable from standard Zircaloy-2 in extrusion behavior. Extrusion constants were calculated from extrusion pressure values taken for each segment of the composite billets.

Even under the most favorable conditions (low C content and high billet temperature), the Th-U alloy exhibited an extrusion constant 11% greater than the Zircaloy-2 (see Table I, No. 1404-2). It was concluded that the Th-U cores in the composite tubes would be 10-20% "stiffer" during extrusion than the Zircaloy-2 end seals. This conclusion was based on an anticipated carbon content of about 1400 ppm and an extrusion temperature of 730°C. Lower carbon contents seemed unlikely in view of the results obtained in the casting development work, while a substantially higher billet temperature would increase the risk of reaction between the copper can and the Zircaloy-2 cladding components.

The extrusion constant of 19 tsi for Zircaloy-2 in rod extrusions at 730°C agrees closely with that obtained for standard Zircaloy-2 in previous work at Nuclear Metals. If the Th-U core alloy were to exceed the Zircaloy-2 end seals in extrusion constant by no more than 20%, the maximum force required for the desired extrusion of the full-scale tubes would approximate 2350 tons. Hence, coextrusion of Zircaloy-2 clad Th-1.5 wt % U alloy could safely be undertaken on a 2750-ton press at the Savannah River Plant.

b. Hot Hardness

Specimens of the Th-U alloy, nickel-free Zircaloy-2, and standard Zircaloy-2 were evaluated for hardness at 620°, 675°, and 730°C. The data shown in Table II show the Th-U to be much harder than the Zircaloys at all three temperatures. The hot hardness values did not correlate well with the extrusion constants shown in Table I. No further effort was made to correlate these observations.

2. Preparation of Prototype Billets

Four composite billets with natural uranium in the core alloy were prepared for extrusion at Savannah River. The first three billets tested two candidate core preshapes (contour of core ends prior to extrusion) designed to produce minimum end taper in the extruded enriched tubes. The fourth prototype was extruded to confirm the choice made in the first round.

a. Design of Billet Components

A tubular billet assembly of the type used in this program is shown in Fig. 2. The billet components were patterned after those used in the recent program on driver tubes for the HWCTR (NMI-7263).

b. Preparation of Components

Thorium-Uranium Cores. Four ingots from the casting development phase of this program were used to provide the cores for the prototype billets. Surface discoloration on the cores caused by machining was removed by abrasion. When all other components for a billet were ready for assembly, the core was scrubbed in an aqueous solution of trisodium phosphate, rinsed in water, and sanded in a lathe with 320-grit emery paper until all surfaces were free of discoloration. The core was then weighed, given a final cleaning with trichlorethylene, and rinsed with acetone.

Zircaloy-2 and Zirconium Components. The Zircaloy-2 forgings used for the inner and outer sleeves were beta heat-treated and worked by extrusion to refine grain size and to minimize forged texture. Normal forged texture and large grain size may result in rough extruded surfaces. Since the structure of the end seals and nose pieces for composite billets is less critical, the Zircaloy-2 and zirconium forgings used for these components were beta-treated without subsequent extrusion.

The machined components successfully passed visual and radiographic inspection for flaws and were measured to ensure conformance to dimensional specifications. They were then cleaned in preparation for assembly into billets.

Copper Components. The outer copper cans were made from commercial seamless tubing 7.10-inches outside diameter with a 0.065-inch-thick wall. The tubing was cut into 16-inch lengths with one end of each length formed to the approximate contour of the internal components (Fig. 2) by spinning over a graphite mandrel. The inner copper cans were made from 2-inch-outside-diameter commercial seamless tubing by drawing the tubing to 1.957-inch-outside-diameter and a 0.065-inch-thick wall. The copper weld plates were machined from 3/8-inch-thick commercial plate.

After initial etching in nitric acid, the copper can components were subjected to a ferrocyanide test for detection of tramp iron particles which could lead to surface depressions in the cladding during extrusion.

c. Assembly of Billets

The copper components were fully prepared well in advance of their use, but the Zircaloy-2 and zirconium components were processed through their etching steps within two hours of billet assembly and the core was given a final cleaning within several minutes of assembly. Immediately following assembly of the billet components, the Zircaloy-2 rear end-seal and zirconium nose piece were Heliarc welded to the Zircaloy-2 sleeves. The welded assembly was evacuated by use of the rear end-seal vent holes, tested for weld integrity with a helium leak detector, and transferred to a vacuum chamber. The vent hole was then sealed off by pin-seal welding in a 0.05-micron vacuum.

The pin-seal weld bead was milled flush to the surface of the rear end seal before the assembly was placed in a copper can. The canning operation was completed by Heliarc welding the copper end plates to the inner and outer copper sleeves. The completed billet was painted on all exposed surfaces with two coats of ethanol-Aquadag in preparation for packing and shipping to Savannah River for extrusion. The coating was prepared by thoroughly mixing 1 part by volume of the commercial Aquadag concentrate with 3 parts ethanol, then straining the mixture through clean cheese cloth.

3. Preparation of Enriched Billets

Three billets with 1.4 wt % ^{235}U (1.505 wt % total U) in the core alloy were prepared to provide tubular fuel elements for irradiation testing.

a. Casting of Core Stock

Three castings with a target composition of 1.4 wt % ^{235}U (1.505 wt % total U) were made to provide cores for the three billets. The castings were made under conditions similar to the last of the prototype castings, except that the uranium was charged in the drilled holes in the top of the thorium in the form of strips about 3-inches long by 5/8-inch wide and 1/8-inch thick. Chemical analyses for the castings are given in Table III.

b. Preparation of Components

Preliminary evaluation of the prototype tubular elements indicated that both billet designs were satisfactory. However, shorter core end tapers were obtained with the short taper preshapes and thus were used for the three enriched billets. Only one design change was made; the length of the core components was decreased to 7.549 ± 0.005 inches, to yield an over-all core length in the enriched tubes more closely approximating the target core length of 108 inches. Descriptions of the enriched cores used in the billets and notes on their final inspection are given in Table IV.

4. Shipment of Billets

Seven composite billets and seven dummy billets were sent to Savannah River.

C. Tube Extrusion and Evaluation

Two extrusion campaigns were conducted at Savannah River: extrusion of the prototype tubular elements for evaluation of the process, and extrusion of the Th-^{235}U elements for irradiation tests in HWCTR.

1. Prototype Th-U Tubes (Natural Uranium)

In the first campaign, one copper, one Zircaloy-2, and three prototype thorium-natural uranium tubular elements were extruded. Two of the prototype tubes were evaluated destructively to determine core and taper shapes, integrity of the clad-to-core bond, and uniformity of the core. The Zircaloy-2 tube and the third prototype were utilized for flow tests.

a. Extrusion

The 2750-ton Watson Stillman press in Building 320-M at Savannah River Plant was used for coextrusion of the Th-U tubes. One copper, one Zircaloy-2, and three prototype Th-U tubes were extruded in April 1964. A maximum force of 2000 tons was used for extruding the prototype billets, which were preheated to 775°C for 18-22 hours (8-10 hours preferred) prior to extrusion. The liner and die temperature was 315°C for this group of tubes. During the extrusions, three of the integral dies and cones cracked but caused no damage to the tubes. Some deviations from the prepared procedure were encountered, such as excessive billet heating time, a time lapse of 2 minutes and 20 seconds from the removal of the billet from the furnace to initiation of extrusion, and malfunction of the temperature recorder. However, the Zircaloy-2 and three prototype tubes were extruded with satisfactory results.

b. Tube Evaluation

Two of the prototype tubes (Nos. 1.1 and 1.2) were evaluated destructively. The two tubes had different billet designs to give different end tapers. The core tips of these tubes were located radiographically and the tubes were subsequently cut up for detailed evaluation. Dimensions of the two tubes were within specifications and showed no evidence of cladding thinning.

Core tip shapes were determined by longitudinal sectioning of the end sections of both tubes. Although both tubes had satisfactory core end tapers, tube No. 1.1 had the shorter one, 5-25/32 inches versus 8-7/16 inches for the front end and 3-11/16 inches versus 7-1/2 inches for the rear end. The billet design used for tube No. 1.1 was therefore adopted for the enriched Th-U fuel elements with a slight reduction in billet core length (from 7.640 to 7.549 inches) to reduce the over-all core length from 109-1/8 inches to the nominal 108 inches.

2. Thorium-Enriched Uranium Tubes

During July 1964, the second group of tubular elements was extruded at Savannah River. This group consisted of two copper tubes, the fourth natural Th-U tube, and three enriched Th-U tubes. Two of the enriched Th-U tubes were satisfactory for irradiation in the HWCTR.

a. Extrusion

A segmented die and cone assembly designed and fabricated by Moczik Tool and Die Works, Detroit, Michigan, was successfully used in this second campaign. The deviations in procedure experienced with the integral die and cone used during the first campaign were corrected in this campaign. Extrusion data for the Th-^{235}U tubes are in Table V.

b. Tube Evaluation

Two of the three candidate tubes, (Nos. 2.1 and 2.3) were acceptable for irradiation. Surface appearance and dimensions were satisfactory. See Table VI for a summary of dimensional characteristics.

After extrusion, both tubes were straightened by gag pressing to within 0.050-inch single-throw bow. Ultrasonic inspection revealed no nonbonds larger than 1/8-inch diameter (the limit of instrument sensitivity). Longitudinal displacement of the core tip around the circumference (shift) and taper of the core ends, as determined by radiography, were similar to prototype tube No. 1.1.

Zircaloy-2 cladding to Th-U core bond strength, and minimum cladding thickness for the irradiation candidates were both satisfactory, based on destructive evaluation of prototype tubes. Zircaloy-2 cladding to Th-U core bond strengths by stud-weld technique on the prototype tubes exceeded the specified 60,000 psi average for 4 studs and the specified minimum 25,000 psi for any one stud. Minimum cladding thickness on the prototype tubes was 0.025-inch.

The third candidate, tube No. 2.2, was unacceptable for irradiation because of ring markings on the inner surface at each end of the tube. These markings were not observed on any of the other tubes and could be evaluated without destroying the tube. The taper at the core ends for this tube was also shorter, as determined by radiography, than for the other two tubes. This tube, together with tube No. 1.4, was given no further evaluation.

II. IRRADIATION

A. Flow Test

The third prototype tube, No. 1.3, was used for long-term flow tests as part of test assembly No. TMT 1-1. Inspection of the assembly following a 97-day flow test in the CMX Power Flow Loop revealed no significant wear or damage to any of the fuel assembly components; the fuel assembly design was considered satisfactory for test irradiation in the HWCTR. The test was run with 260°C water having a pH of 10 at a flow rate of 150 gpm.

B. HWCTR Irradiation Results

The two Th-^{235}U fuel assemblies were operated in the HWCTR under a test permit; their histories are summarized below.

	TMT 1-2	TMT 1-3
Start of irradiation	8/25/64	8/25/64
End of Irradiation	12/1/64	12/1/64
Maximum accumulated exposure, MWD/Te	3578	3489
Maximum specific power,* MW/Te	49.1	47.8
Maximum central metal temperature,* °C	468	462

*Time-weighted average values.

Irradiation of the two assemblies was interrupted when the HWCTR operation was terminated.

Irradiation data were calculated by the ROTAH IBM program for fuel calculations. The time-weighted average values for core temperature, surface temperature, surface heat flux, and specific power for the entire irradiation period are given in Table VII for TMT 1-2 and Table IX for TMT 1-3. For the hottest region of each assembly, all data from the first exposure interval to the last are presented (Table VIII for TMT 1-2 and Table X for TMT 1-3). Temperatures given are weighted over each exposure interval and do not reflect all the temperature variations that may have occurred during the period.

Exposure intervals used for all the ROTAH IBM calculations described above are given in Fig. 3. Rather than record all of the changes for all of the fuel assemblies in the HWCTR, it is assumed that the power in each assembly is proportional to total reactor power and, thus, assembly exposure is proportional to reactor exposure. For this reason, an equivalent time interval (Fig. 3, column 4) based on a constant reactor power is calculated. This may include periods when the reactor is shut down and also periods when conditions are changing, such as startup and power ascension.

Power levels for the irradiation period of the Th-^{235}U fuel assemblies are in Fig 4. Shown are the daily power levels which have been averaged for the ROTAH IBM data within the equivalent time intervals described above.

C. Postirradiation Inspection

Preirradiation measurements of the inside and outside diameters of both irradiation candidates, tube No. 2.1 (Assembly TMT 1-2) and tube No. 2.3 (Assembly TMT 1-3) were made prior to delivery to the HWCTR. Following irradiation of the two test elements in the HWCTR, they were removed and postirradiation measurements were made on one tube from Assembly TMT 1-2. Comparison of the pre- and postirradiation data (Fig. 3) indicates that the volume change in the region of maximum exposure and core temperature was about 0.8% after an accumulated exposure of 3500 MWD/Te. The volume change resulted from an increase of about 0.005-inch of the OD and an increase of about 0.001-inch of the ID of the tube. Since operation of the HWCTR was terminated, no further irradiation of the two Th-^{235}U assemblies is planned. Both test assemblies have been stored in the receiving basin for off-site fuel (RBOF) at the Savannah River Plant.

TABLE I

Extrusion Constants for Th-U and Zircaloy-2

	Chemical Analysis of Th-U[a]			Extrusion Constant K		Ratio of Extrusion Constants, Relative to Zr-2, %
Extrusion Number	Uranium, wt %	Carbon, ppm	Billet Temp, °C	Zr-2,[b] tsi	Th-U, tsi	$\frac{K_{Th-U} - K_{Zr-2}}{K_{Zr-2}}$ (100)
1404-1	1.50	520	675	19.3	22.6	17
1404-2	1.53	620	730	17.9	19.9	11
1429-1 (core A)	1.64	1390	730	19.4	22.8	18
1429-1 (core B)	1.50	3050	730	19.4	25.8	33

Extrusion	NM 300-ton press
Liner:	2.040-inch bore; 480°C
Die:	0.534-inch opening; 480°C
Cutoff:	Copper, at same temperature as billet
Lubricant:	Aquadag on liner, die and billet before heating; Oildag on liner and die just before extrusion
Ram speed:	16 inches/minute
Extrusion reduction:	14.6:1

(a) Analyses made on samples from mid-length of Th-U after extrusion.
(b) Average of front and rear cylinders of nickel-free Zircaloy-2.

TABLE II

Hot Hardness of Th-U and Zircaloy-2

Alloy[a]	DPH Number 620°C	675°C	730°C
Th-1.55 wt % U with 1350 ppm carbon	42	29	23
Th-1.45 wt % U with 1520 ppm carbon	41	30	24
Nickel-free Zircaloy-2	28	17	12
Standard Zircaloy-2	23	16	12

(a) Composition of Th-U specimens based on analysis just below the hot top from which the specimens were machined. Nickel-free Zircaloy-2 from same stock used for rod extrusions. Standard Zircaloy-2 from inner sleeve stock, Ingot No. HZC-1677.

TABLE III

Chemical Analyses for Enriched Castings

Casting Number	Total U, wt %[a] Top	Bottom	Carbon, ppm Top	Bottom
TX-1448[b]	1.59	1.58	1180	1010
TX-1451	1.53	1.53	2390	3030
TX-1453[c]	1.53	1.53	760	910

(a) Oralloy containing 93% ^{235}U used in melting; multiply by 0.93 to obtain wt % ^{235}U.

(b) A sample drilled from the midwall about 1/2 inch below the top of the hot top analyzed 1.59 wt % total U and 1140 ppm C.

(c) Two samples turned from the midlength of the cropped casting when close to the final OD and ID for a core component analyzed 1.56 wt % total U and 1040 ppm C for the outside and 1.55 wt % total U and 1040 ppm C for the inside.

TABLE IV

Description of Enriched Billet Cores

Enriched Billet Number	Casting Number	Composition: Total U, wt %	Composition: Carbon, ppm	Core Weight, grams	Results of Final Inspection[a]
2-1	TX-1448	1.58	1140	39,600	Several pores less than 0.02-inch diameter scattered over outside surface near rear
2-2	TX-1451	1.53	2710	39,400	Numerous pores less than 0.02-inch diameter on ends and outside surface.
2-3	TX-1453	1.53	840	39,710	Three pores less than 0.02-inch diameter on rear end.

(a) Final measurements indicated all three cores were within the dimensions specified (length specified for enriched cores was 7.549 ±0.005 inch).

TABLE V

Extrusion Data for Group of Enriched Th-U Tubes

Tube No.	1.4	2.1	2.2	2.3
Material	Th-1.56 wt % U (natural)	Th-1.58 wt % U (93% ^{235}U)	Th-1.53 wt % U (93% ^{235}U)	Th-1.53 wt % U (93% ^{235}U)
Casting No.	TX-1454	TX-1448	TX-1451	TX-1453
Date extruded	7/9/64	7/9/64	7/9/64	7/9/64
Press capacity, tons	2750	2750	2750	2750
Ram speed, in./min	12	12	12	12
Tool diameter, inches				
Liner, ID	7.200	7.200	7.200	7.200
Die,[(a)] ID	2.573	2.573	2.573	2.573
Mandrel OD	1.831	1.831	1.831	1.831
Tool temperature, °C				
Liner & die	370	370	370	370
Mandrel & cutoff	370	370	370	370
Cut-off material	Copper	Copper	Copper	Copper
Lubricant	Aquadag prior to heating-Oildag just prior to extrusion			
Billet heating				
Furnace	Lindberg 40 Kw pot furnace			
Temp,[(b)] °C	760	760	760	760
Atmosphere	Reducing (graphite sleeve around billet)			
Total time	8 hr-30 min	8 hr-45 min	9 hr	9 hr-15 min
Reduction ratio	14:1	14:1	14:1	14:1
Extrusion force, tons				
End seals	1950	1900	1900	1900
Core	1500	1500	1500	1500
Extrusion constant K				
End seals, tsi	19.5	19	19	19
Core, tsi	15	15	15	15

(a) Die & cone assembly.
(b) Read at inside wall of billet before removal from furnace.

TABLE VI

Summary of Dimensional Characteristics of Prototype and Enriched Tubes

Tube No.	0.1(a)	1.1(b)	1.2(b)	1.3(a)	1.4(c)	2.1(d)	2.2(e)	2.3(d)
	Zircaloy	Natural-U				Enriched-U		
Taper, in. Front	NA	5-25/32	8-7/16	(f)	Not Evaluated	(f)	Reject Tube - Not Evaluated	(f)
Taper, in. Rear		3-11/16	7-1/2					
Shift, in. Front	NA	5/16	5/8	(f)		(f)		(f)
Shift, in. Rear		19/32	1-15/16					
Shift + taper, in. Front	NA	6-3/32	9-1/16	(f)		(f)		(f)
Shift + taper, in. Rear		4-9/32	9-7/16					
OD, wt % Cu, in. avg(g)	2.571	2.572	2.569	2.566		-		-
ID, wt % Cu, in. avg(g)	1.835	1.832	1.831	1.829		-		-
OD, wt % Cu, in. avg(h)	2.547	2.548	2.545	2.542		2.540		2.539
ID, wt % Cu, in. avg(h)	1.844	1.841	1.840	1.837		1.830		1.828
Bow, before straightening, in. max	3/16	15/16	9/16	5/16		-		-
Bow, after straightening, in. max	1/16	-	-	1/16		less than 3/32		less than 3/32
Wall thickness, in. avg	0.351	0.354	0.352	0.348		0.355		0.356
min	0.346	0.349	0.345	0.342		0.352		0.355
max	0.357	0.358	0.358	0.355		0.356		0.358
Outer cladding, in. avg	NA	0.032	0.034	-		-		-
min	NA	0.030	0.030	-		-		-
max	NA	0.035	0.035	-		-		-
Core, in. avg	NA	0.286	0.285	-		-		-
min	NA	0.280	0.280	-		-		-
max	NA	0.290	0.300	-		-		-
Inner cladding, in. avg	NA	0.031	0.031	-		-		-
min	NA	0.030	0.030	-		-		-
max	NA	0.035	0.035	-		-		-

(a) Tubes 0.1, and 1.3 were used for flow testing.
(b) Tubes 1.1, and 1.2 were destructively examined.
(c) Tube 1.4 was used as a dummy tube just prior to extrusion of the three enriched tubes. No evaluation of this tube was made.
(d) Tubes 2.1 and 2.3 were designated as irradiation candidates and were irradiated in the HWCTR.
(e) Tube 2.2 was unacceptable for irradiation because of ring markings on the inner surface at each end of the tube. No further evaluation of this tube was made.
(f) End taper and shift for tubes 1.3, 2.1, and 2.3 were similar to tube 1.1, as determined by radiography. Same billet design as for tube 1.1 was used.
(g) These dimensions are based on a 4-1/2-mil copper sheath on the ID and a 12-mil copper sheath on the OD.
(h) These dimensions are averaged over the uniform core and were taken prior to final etching of tubes. Approximately 1-1/2 mils is removed from each surface during etching.

TABLE VII

Time-Weighted Average Values for Th-^{235}U Assembly No. TMT 1-2

Layer	Core Temp., °C	Surface Temperature, °C Inner	Surface Temperature, °C Outer	Surface Heat Flux[(a)] Inner	Surface Heat Flux[(a)] Outer	Specific Power[(b)]
1	188.4	183.2	183.1	0.953E 04	0.879E 04	1.1
2	207.4	186.9	186.7	0.373E 05	0.344E 05	4.4
3	228.7	191.3	190.8	0.684E 05	0.631E 05	8.1
4	253.3	196.5	195.8	0.104E 06	0.962E 05	12.4
5	281.2	202.6	201.6	0.145E 06	0.134E 06	17.3
6	312.3	209.5	208.2	0.190E 06	0.176E 06	22.7
7	345.7	217.2	215.2	0.239E 06	0.221E 06	26.5
8	379.9	225.4	223.2	0.289E 06	0.267E 06	34.5
9	412.2	233.5	230.9	0.337E 06	0.311E 06	40.1
10	439.6	240.8	237.8	0.376E 06	0.347E 06	44.7
11	458.3	246.5	243.3	0.401E 06	0.370E 06	47.8
12	467.5	250.4	247.0	0.412E 06	0.380E 06	49.1
13	468.5	252.7	249.1	0.410E 06	0.378E 06	48.8
14	462.4	253.5	249.8	0.397E 06	0.366E 06	47.3
15	449.7	252.8	249.2	0.374E 06	0.345E 06	44.5
16	430.4	250.7	247.1	0.340E 06	0.314E 06	40.5
17	404.5	247.1	243.6	0.297E 06	0.274E 06	35.4
18	372.4	242.0	238.8	0.245E 06	0.227E 06	29.2
19	335.7	235.8	232.9	0.187E 06	0.173E 06	22.3
20	296.7	228.9	226.3	0.127E 06	0.117E 06	15.1
21	260.4	222.3	220.0	0.718E 05	0.663E 05	8.6

(a) pcu/(hr)(ft^2). Example: 0.953E 04 = 0.953×10^4.
(b) Watts/gram of core material (Th-^{235}U).

TABLE VIII

Variables Versus Specific Exposure for Hottest Region of Th-^{235}U Assembly No. TMT 1-2

Layer 13 (76 inches from top of tube)

Spec Expos (a)	Core Temp (b)	Channel Temperature (b)		Surface Temperature (b)		Surface Heat Flux (c)		Volumetric Heat Generation (d)	Specific Power (e)
		Inner	Outer	Inner	Outer	Inner	Outer		
284.2	504.2	198.3	197.5	259.3	255.5	0.467E 06	0.431E 06	0.372E 08	55.6
524.0	497.3	198.6	197.7	258.1	254.3	0.456E 06	0.421E 06	0.363E 08	54.3
759.4	494.0	198.8	197.8	257.6	253.8	0.451E 06	0.416E 06	0.359E 08	53.7
986.4	486.6	199.1	198.2	256.4	252.6	0.439E 06	0.405E 06	0.349E 08	52.2
1204.9	477.9	199.8	198.8	255.1	251.5	0.424E 06	0.391E 06	0.337E 08	50.5
1422.0	483.5	200.0	198.9	256.4	252.6	0.432E 06	0.399E 06	0.344E 08	51.5
1553.6	478.5	201.2	200.0	256.3	252.5	0.423E 06	0.390E 06	0.337E 08	50.4
1618.0	465.8	200.0	199.0	252.8	249.2	0.405E 06	0.373E 06	0.322E 08	48.2
1813.1	464.8	199.4	198.3	252.1	248.4	0.404E 06	0.373E 06	0.322E 08	48.1
1966.4	466.8	199.8	198.7	252.8	249.2	0.407E 06	0.375E 06	0.324E 08	48.4
2058.0	464.7	200.2	199.1	252.7	249.1	0.403E 06	0.372E 06	0.321E 08	47.9
2214.8	455.4	200.8	199.6	251.3	247.7	0.387E 06	0.357E 06	0.308E 08	46.1
2370.9	455.6	201.1	200.0	251.6	248.0	0.387E 06	0.357E 06	0.308E 08	46.1
2531.5	446.9	201.8	200.6	250.4	246.8	0.373E 06	0.344E 06	0.297E 08	44.4
2690.7	458.4	201.9	200.6	252.8	249.1	0.390E 06	0.360E 06	0.311E 08	46.5
2764.6	450.7	202.5	201.2	251.7	248.0	0.378E 06	0.348E 06	0.301E 08	45.0
3040.0	420.1	193.9	193.2	238.4	235.5	0.343E 06	0.316E 06	0.273E 08	40.8
3290.8	468.1	198.1	197.1	251.5	247.9	0.411E 06	0.380E 06	0.328E 08	49.0
3349.6	457.4	199.5	198.5	250.5	247.0	0.393E 06	0.362E 06	0.313E 08	46.7
3560.1	462.4	199.8	198.8	251.7	248.2	0.400E 06	0.369E 06	0.318E 08	47.6
AVERAGE	468.5			252.7	249.1	0.410E 06	0.378E 06		48.8

(a) Watt-days/gram.
(b) All temperatures in °C.
(c) pcu/(hr)(ft^2). Example: 0.467E 06 = 0.467 x 10^6
(d) pcu/(hr)(ft^3). Example: 0.372E 08 = 0.372 x 10^8
(e) Watts/gram of core material (Th-^{235}U).

TABLE IX

Time-Weighted Average Values for Th-^{235}U Assembly No. TMT 1-3

Layer	Core Temp, °C	Surface Temperature, °C Inner	Surface Temperature, °C Outer	Surface Heat Flux(a) Inner	Surface Heat Flux(a) Outer	Specific Power(b)
1	188.3	183.1	183.1	0.930E 04	0.858E 04	1.1
2	206.9	186.9	186.6	0.364E 05	0.336E 05	4.3
3	227.8	191.2	190.7	0.668E 05	0.616E 05	7.9
4	251.8	196.4	195.6	0.102E 06	0.939E 05	12.1
5	279.2	202.4	201.3	0.142E 06	0.131E 06	16.8
6	309.7	209.3	207.8	0.186E 06	0.172E 06	22.1
7	342.5	216.9	215.1	0.234E 06	0.216E 06	27.8
8	376.0	225.0	222.7	0.283E 06	0.261E 06	33.6
9	407.8	233.0	230.3	0.329E 06	0.303E 06	39.0
10	434.7	240.3	237.2	0.367E 06	0.339E 06	43.6
11	453.1	246.0	242.6	0.392E 06	0.362E 06	46.5
12	462.1	249.9	246.3	0.402E 06	0.371E 06	47.8
13	463.2	252.2	248.4	0.400E 06	0.369E 06	47.5
14	457.3	253.0	249.1	0.388E 06	0.358E 06	46.0
15	444.9	252.3	248.5	0.365E 06	0.337E 06	43.3
16	426.0	250.3	246.5	0.332E 06	0.307E 06	39.5
17	400.6	246.7	243.1	0.290E 06	0.268E 06	34.5
18	369.2	241.7	238.4	0.240E 06	0.221E 06	28.5
19	333.2	235.5	232.5	0.183E 06	0.169E 06	21.7
20	295.0	228.7	226.0	0.124E 06	0.115E 06	14.7
21	259.4	222.2	219.8	0.701E 05	0.647E 05	8.3

(a) pcu/(hr)(ft^2). Example: 0.930E 04 = 0.930 x 10^4
(b) Watts/gram of core material (Th-^{235}U).

TABLE X

Variables Versus Specific Exposure for Hottest Region of Th-^{235}U Assembly No. TMT 1-3

Layer 13 (76 inches from top of tube)

Spec Expos[a]	Core Temp[b]	Channel Temperature[b]		Surface Temperature[b]		Surface Heat Flux[c]		Volumetric Heat Generation[d]	Specific Power[e]
		Inner	Outer	Inner	Outer	Inner	Outer		
273.5	494.0	198.1	197.2	257.5	253.6	0.450E 06	0.416E 06	0.357E 08	53.5
503.5	486.4	198.3	197.4	256.1	252.2	0.438E 06	0.404E 06	0.347E 08	52.0
732.6	487.4	198.7	197.7	256.6	252.7	0.439E 06	0.405E 06	0.348E 08	52.1
953.5	480.2	199.0	198.1	255.4	251.6	0.427E 06	0.394E 06	0.338E 08	50.7
1166.1	471.7	199.7	198.7	254.2	250.4	0.413E 06	0.381E 06	0.327E 08	49.0
1377.4	477.2	199.9	198.8	255.5	251.6	0.421E 06	0.389E 06	0.334E 08	50.0
1506.0	473.3	201.1	200.0	255.7	251.8	0.414E 06	0.382E 06	0.327E 08	49.1
1568.2	458.0	199.8	198.7	251.5	247.7	0.391E 06	0.361E 06	0.310E 08	46.5
1758.7	459.8	199.3	198.2	251.5	247.7	0.395E 06	0.365E 06	0.313E 08	46.9
1908.0	460.8	199.7	198.6	252.0	248.1	0.396E 06	0.366E 06	0.314E 08	47.0
1997.1	458.7	200.1	199.0	251.9	248.1	0.392E 06	0.362E 06	0.311E 08	46.6
2149.7	449.6	200.6	199.5	250.4	246.7	0.377E 06	0.348E 06	0.299E 08	44.8
2301.6	449.8	201.1	199.9	250.8	247.1	0.377E 06	0.348E 06	0.299E 08	44.8
2456.9	439.7	201.5	200.3	249.1	245.5	0.360E 06	0.333E 06	0.285E 08	42.8
2610.9	451.0	201.6	200.4	251.5	247.7	0.378E 06	0.349E 06	0.299E 08	44.9
2682.5	444.4	202.3	201.0	250.7	246.9	0.367E 06	0.338E 06	0.290E 08	43.5
2954.2	418.9	194.2	193.4	239.1	236.0	0.339E 06	0.313E 06	0.268E 08	40.2
3203.1	468.4	198.5	197.5	252.9	249.0	0.409E 06	0.378E 06	0.324E 08	48.6
3261.7	458.6	200.1	199.0	252.1	248.3	0.392E 06	0.361E 06	0.310E 08	46.5
3471.2	463.4	200.4	199.3	253.3	249.5	0.399E 06	0.368E 06	0.316E 08	47.3
AVERAGE	463.2			252.2	248.4	0.400E 06	0.369E 06		47.5

(a) Watt-days/gram.
(b) All temperatures in °C.
(c) pcu/(hr)(ft^2). Example: 0.450E 06 = 0.450 x 10^6.
(d) pcu/(hr)(ft^3). Example: 0.357E 08 = 0.357 x 10^8.
(e) Watts/gram of core material (Th-^{235}U).

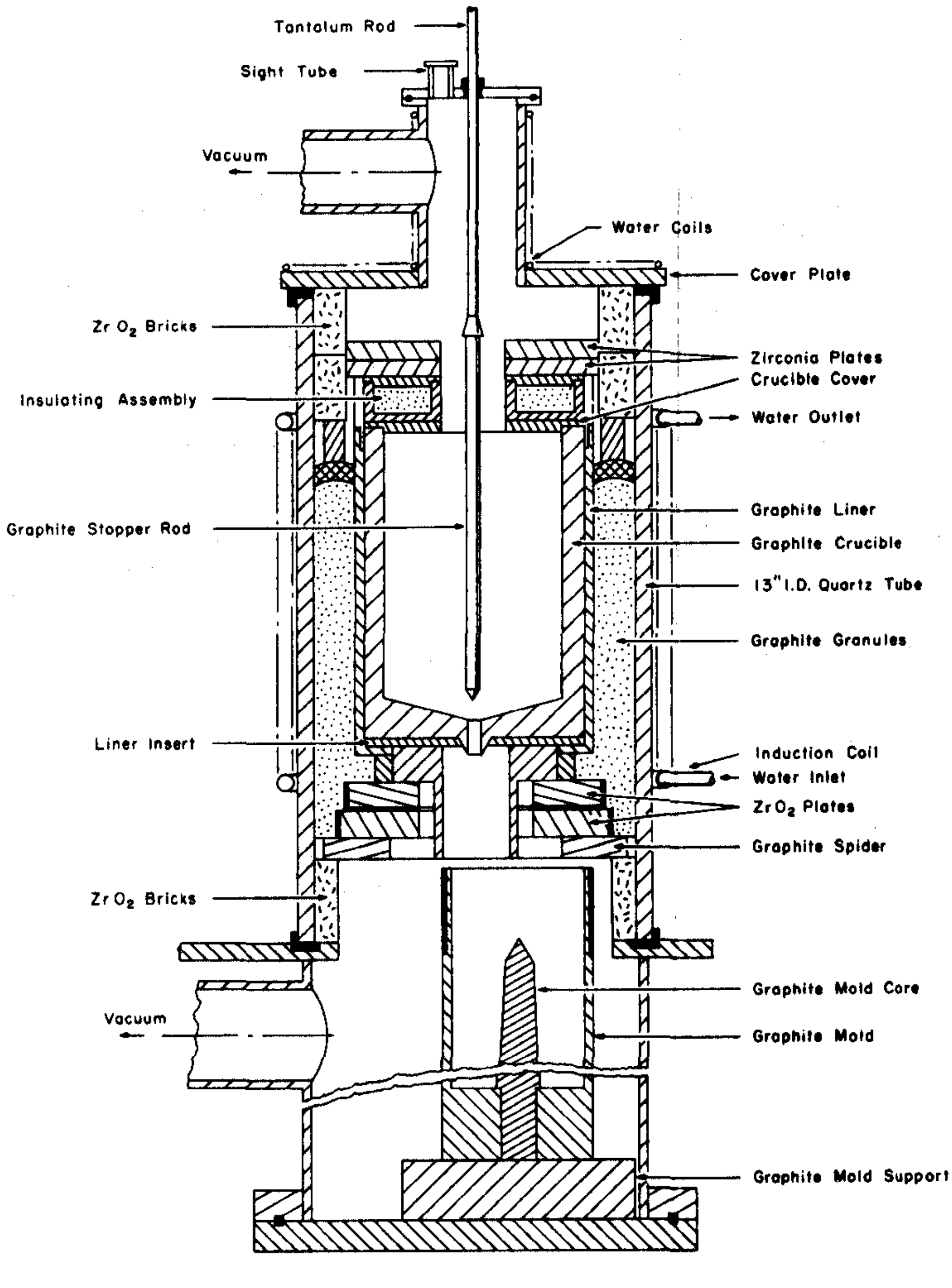
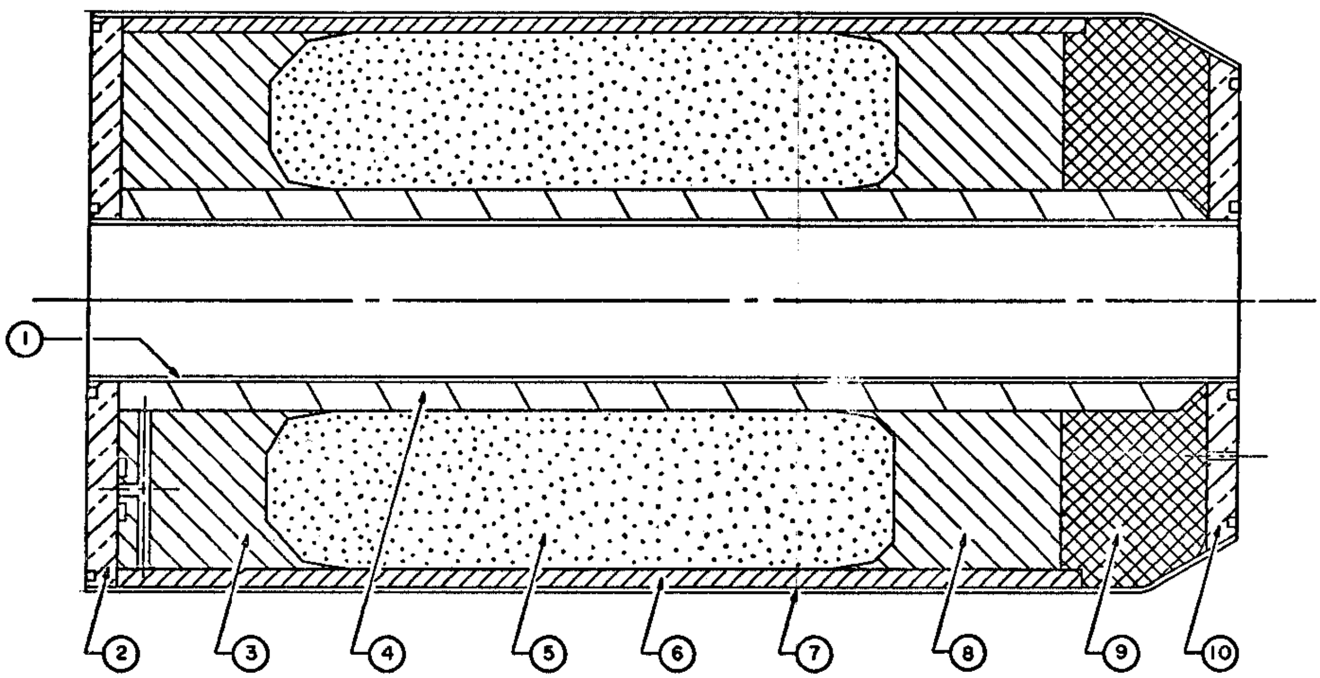


FIG. 1 BOTTOM-POUR VACUUM INDUCTION MELTING FURNACE



1. Cu Inner Can
2. Cu Rear Weld Plate
3. Zircaloy - 2 Rear End Seal
4. Zircaloy - 2 Inner Sleeve
5. Th-U Core
6. Zircaloy - 2 Outer Sleeve
7. Cu Outer Can
8. Zircaloy - 2 Front End Seal
9. Zr Nose
10. Cu Front Weld Plate

FIG. 2 COMPOSITE BILLET ASSEMBLY FOR THORIUM-URANIUM TUBULAR ELEMENTS

Real Time Interval	Reactor Differential Exposure, MWD	Reactor Power, MW	Equivalent Time Interval, days	HWCTR Cycle
(1964) 8/25 - 8/31	241.27	49.58	4.87	H-2.5
9/1 - 9/5	211.40	50.23	4.21	↓
9/5 - 9/9	211.40	50.57	4.18	
9/15 - 9/19	204.40	49.33	4.14	
9/20 - 9/24	207.00	50.16	4.13	
9/24 - 9/28	207.00	51.50	4.02	
9/28 - 9/30	131.77	52.89	2.49	
10/1 - 10/3	64.37	50.49	1.27	
10/3 - 10/7	196.13	50.74	3.87	
10/8 - 10/12	154.74	51.25	3.02	
10/13 - 10/16	92.55	50.81	1.82	
10/16 - 10/19	166.00	51.21	3.24	
10/19 - 10/22	166.00	51.41	3.23	
10/22 - 10/26	177.84	51.51	3.45	
10/26 - 10/29	177.84	54.46	3.27	
10/29 - 10/31	85.13	54.36	1.57	
11/10 - 11/18	283.75	44.04	6.44	H-2.6
11/18 - 11/23	269.00	55.08	4.88	↓
11/23 - 11/25	66.30	55.24	1.20	
11/26 - 12/1	234.08	55.51	4.22	

REACTOR LOCATION

TMT 1-2 in Position 40

TMT 1-3 in Position 37

FIG. 3 FUEL EXPOSURE INTERVALS IN HWCTR

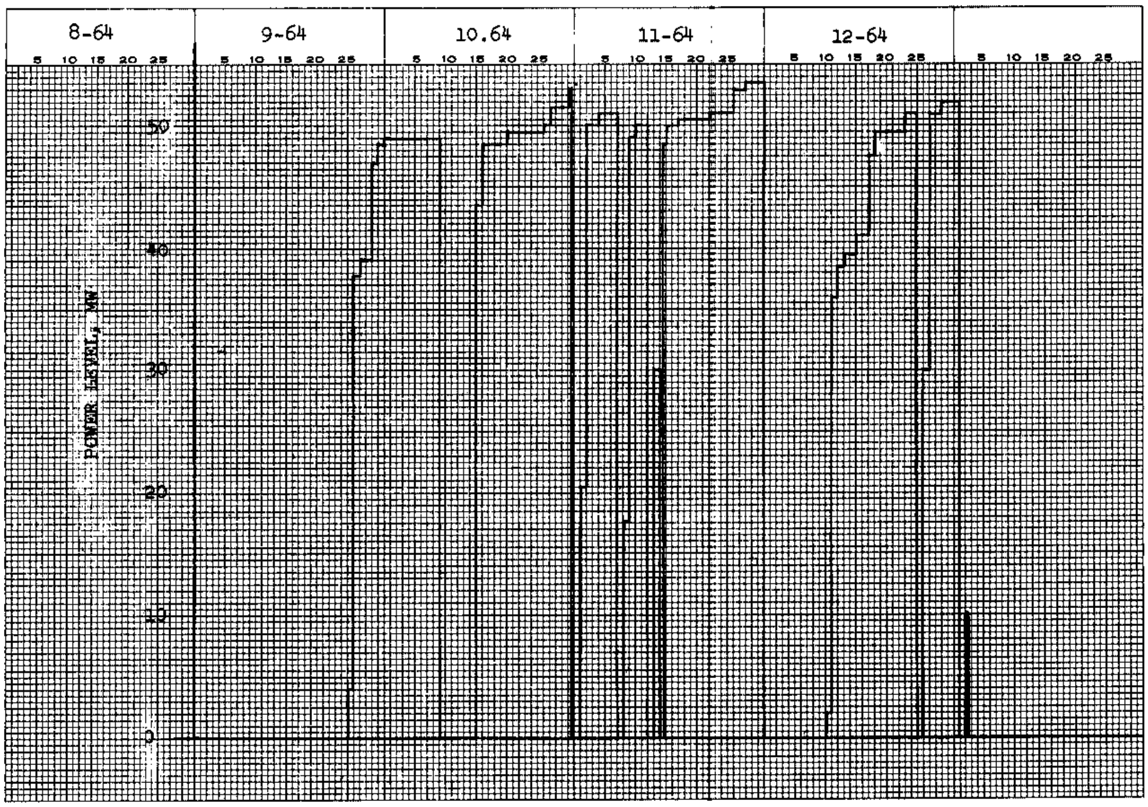


FIG. 4 HWCTR POWER LEVELS DURING IRRADIATION OF Th-^{235}U FUEL ASSEMBLIES

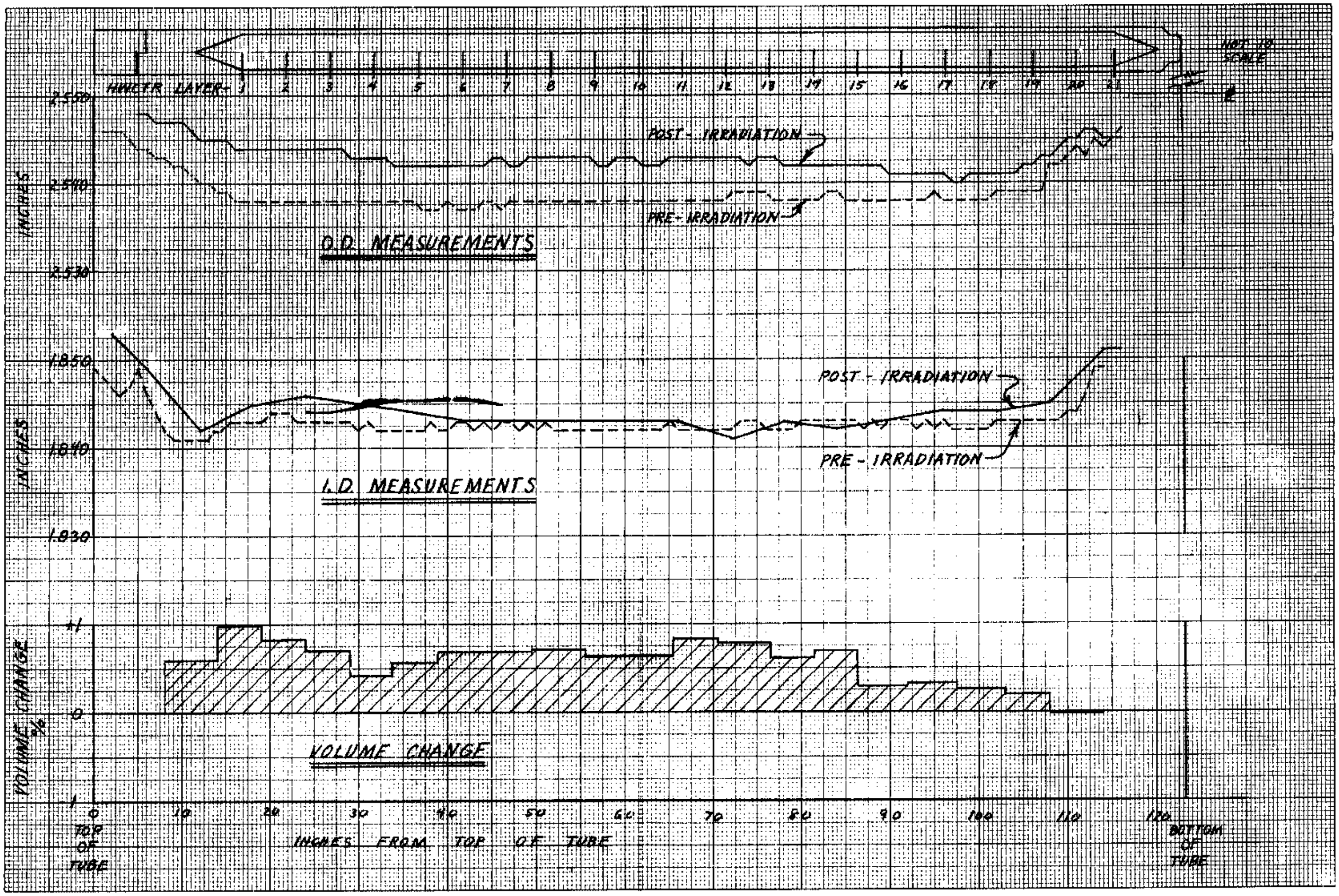
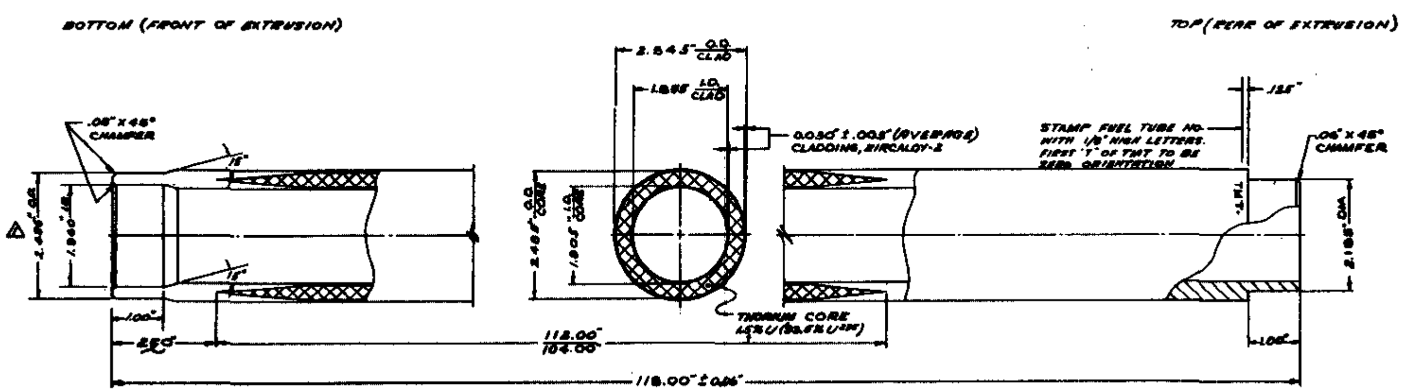


FIG. 5 PRE- AND POSTIRRADIATION MEASUREMENTS OF Th-^{235}U TUBE NO. 2.1 (ASSEMBLY TMT-1-2)



NOTES:

1. MAX. BOW: .010"/FT, 3/32" OVERALL
2. AS EXTRUDED SURFACE FINISH: 125/ LONGITUDINAL, 250/ CIRCUMFERENTIAL
3. MAX. OVALITY: .010"
4. DETAILED SPECIFICATIONS LISTED IN DPW-64-149
5. LOCATION OF BOTTOM CORE TIP MUST BE KNOWN ± .12"

FIG. 6 THORIUM METAL TUBE