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AEC RESEARCH AND DEVELOPMENT REPORT

**THORIUM-1.4 wt% ²³⁵URANIUM METAL FUEL TUBES -
FABRICATION AND IRRADIATION IN HWCTR**

Edited by S. R. Nemeth

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Supplement

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FABRICATION AND IRRADIATION IN HWOTR

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ABSTRACT

Three thorium-1.4 wt % ²³⁵uranium 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.

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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-²³³U fuel cycle. Fabrication of several Th-²³³U 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).

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 % ²³⁵U 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-²³⁵U 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.

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. Details of the background and design of this test are in Appendix A. 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 (see Appendix D) which led to extrusion of the Th- ^{235}U subsequently used for irradiation tests in the HWCTR. Specifications for the enriched tubes produced during this program are in Appendix B, and the Test Irradiation Description is in Appendix C-1.

Following preirradiation inspection, the two Th- ^{235}U fuel elements were irradiated in the HWCTR under a test permit, included as Appendix E. 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 and therefore was not used.

b. Crucibles and Molds

Selection of Crucible Material. Coated graphite crucibles were selected, after giving some consideration to the use of ceramic crucibles for the melting of thorium in order to avoid the problem of carbon pickup encountered in melting in graphite. The ceramic crucibles that were considered were BeO , ThO_2 , and ZrO_2 . 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.

Preparation of Crucibles. Dense graphite (grade 800-S) melting crucibles, 8-3/16-inch ID X 12 inches deep, were brush-coated with a heavy slurry of CaO -stabilized Zirconia wash^(a). Prior to being coated, the stopper rods (originally CR-grade graphite, later changed to AUC-grade) and the inside walls of the crucibles were cleaned with a NaOH solution and rinsed with water, to ensure that the coating would completely adhere to the graphite. Before insertion in the melting furnace, the crucibles were air-dried and then oven-baked at 200°C.

(a) T.A.M. Stabilized Zirconia Wash A slurry in water.

The melting crucible was contained within a thin graphite liner to (1) prevent any penetration of liquid thorium alloy beyond the crucible, and (2) facilitate the changing of crucibles. Graphite granules were packed between the graphite liner and the quartz tube for insulation.

Crucibles 12 inches high were adequate for 175-pound melt charges. However, the form and shape of the thorium melting stock was such that when the charge weights were increased to 200 pounds it was necessary to lengthen the crucible by attaching a 3-inch-long graphite sleeve to contain the solid charge.

Molds. The melts were bottom-poured from the crucible (by lifting an internal stopper rod) into a bare graphite (grade 800-8) mold whose top was about 5 inches below the bottom of the melting crucible. Prior to use, the mold for the enriched castings (Fig. 2) and its core were vacuum degassed to 1700-1800°C to eliminate volatiles that might form gas or react with the liquid metal being poured. During the melting cycle, the mold was preheated only by radiation from the crucible assembly. The bottom of the mold was 4 inches thick to promote rapid directional solidification of the metal from bottom to top. The diameter of the bottom portion of the furnace was such that the mold was placed so that the pour stream entered the mold nearer to the core than the mold wall. Insulation of the top portion of the mold with a wrapped layer of Fiberfax assisted in maintaining a pool of liquid metal to supply the feeder head and thereby (1) form the shrinkage cavities as near the top as possible, and (2) minimize the size of the shrinkage cavities.

c. Charge Materials

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

- o Vacuum-melted ingot hot tops from Davison Chemical Co., mostly about 8-1/4-inches diameter X 2 to 6-inches long. These pieces could be identified and individual carbon analyses were known.
- o Fuel slugs, 1 to 1-1/4 inches diameter X 6-inches long from National Lead Company of Ohio (individual carbon analyses not known but inferred from analyses of similar material).
- o 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 utilized in the form of 1-inch diameter short-length cylinders.

In order to arrange the charge most judiciously in the melting crucible, it was necessary to cut the large hot-top thorium sections in half. One-inch diameter uranium cylinders were placed in holes drilled in the top of the heavy thorium pieces. In this way, superheat of the initial molten uranium pool and the consequent carbon pickup were minimized. The metal was charged into the crucible carefully to avoid scratches or punctures in the ceramic coating. After the first few melts, Th-U alloy hot tops, etc., generated in this program were recycled.

d. Heating Schedule

In the melting of these alloys it is desirable to use rapid heating with a minimum 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.

<u>Time,</u> <u>minutes</u>	<u>Input</u> <u>Power,</u> <u>kw</u>	<u>Vacuum,</u> <u>microns</u>	<u>Melt</u> <u>Temperature,</u> <u>°C</u>	<u>Remarks</u>
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.

2. Prototype Castings

For subsequent assembly into a billet for extrusion, it was necessary to produce castings which would clean up on machining to 6.59-inches OD, 2.69-inches ID, and 8-inches long. In order to obtain sound billets 8-inches long, it was necessary to pour castings 12 inches long to allow for the solidification shrinkage cavities. For the thorium alloys used (about 1.5 wt % uranium) no serious composition segregation problem was encountered. This could be explained by the relatively small temperature spread between the liquidus and solidus compared with that for higher alloys. Homogeneity was promoted by the rapid solidification effected by the thick-bottomed mold (Fig. 2). The reaction between the liquid thorium alloy and the bare graphite mold was limited to a very thin skin, presumably of thorium carbide, which adhered to the mold walls after removal of the casting from the mold. The mold-metal reaction was minimized by rapid solidification of the thorium alloy in contact with the graphite because of the low heat of fusion and low heat content of thorium. This rapid solidification of thorium also resulted in the formation of cold shuts and transverse laps on the casting surfaces, necessitating the removal of considerable metal by machining. These surface conditions are often found in conjunction with small, clean, spherical, subsurface gas holes extending deeper than the surface flaws. It is hypothesized that these small gas holes originated from a metal-mold reaction. Time was not available for investigation of this problem.

a. Prototype Melt Conditions

A summary of the conditions and results of the prototype melts is shown in Table I.

Initially, a 175-pound charge weight was selected for the nominal 7.0-inch diameter casting of a 1.5 wt % uranium alloy. The first casting (TX-1370) was unsatisfactory because some metal leaked through the stopper rod-crucible seal before the melt was poured. Subsequent examination of the crucible indicated erosion and attack of both the tapered portion of the stopper rod and the crucible seat at the location of the leak. The attack was attributed to (1) overheating of the crucible in this particular area, because no charge metal had been placed in the immediate proximity; (2) insufficient ceramic coating between stopper rod and seat, allowing a metal-graphite reaction and subsequent penetration of the seal. To correct this problem, in all subsequent melts the stopper rods were machined from a denser grade (AUC) of graphite, more coating was applied on the stopper rod, and the thorium charge metal was placed adjacent to the seal to insure more uniform heating.

In a duplicate 175-pound melt (TX-1373), the casting outer and inner surfaces showed transverse laps typical of thorium alloys, and roughness due to metal splashed during the pouring of the metal.

Upon sectioning the casting, two secondary shrink holes, about 1/2-inch diameter, were found about 3-1/2-inches from the bottom and nearer the inside than the outside wall. The primary shrinkage cavities (pipe) were adjacent to and above the pointed portion at the top of the graphite core.

Two changes were made for the next melt (TX-1382): (1) the mold and core design was modified with the mold inside diameter increased to 7.5 inches and the core tapered from 2.2-inch diameter at the bottom to 1.8-inch diameter at the top, and (2) the melt charge was increased to 190 pounds. With the thicker casting, both inside and outside surfaces cleaned up during machining. One very small inclusion, however, was noted on the inner surface of the machined sleeve. The use of a tapered core improved directional solidification, eliminating the secondary shrinkage defects, whereas the primary shrinkage cavities remained in the same area as previously.

For melt No. TX-1394, the diameter of the tapered core was uniformly decreased by 0.1 inch. Also, the uranium content of the alloy was increased to 1.61 wt % U. The casting appeared normal except for some graphite granules attached to the bottom surface. It appears that, just prior to the melting cycle, a small quantity of graphite granules was sucked through a crack in the upper zirconia supporting plate and fell into the mold. This caused a considerable increase in the carbon content of this casting. The casting surfaces appeared sound after machining. Radiography indicated two small spots in the casting wall, probably representing inclusions of graphite granules.

The next three castings (TX-1407, 1414, and 1419), with natural uranium for the prototype billet cores, were made in an identical manner as TX-1394, with the melt charge increased to 200 pounds. This larger charge increased the over-all casting length to about 12 inches, thereby increasing the length of the useful portion of the casting. With the larger melt charge, more of the charge metal was above the field of the heating coil and, as a result, the crucible skulls were somewhat larger. After machining, all of these castings had good surfaces, and the radiographs indicated no internal defects in the casting walls. No changes were made in the general procedures used for the three enriched castings and for an additional natural casting for a prototype (TX-1454) extrusion. However, based on revised calculations for irradiation, total uranium content was reduced to 1.505 wt % (1.40 wt % ²³⁵U).

b. Casting Analyses

Carbon Pickup. Each casting was sampled about 1/4-inch from the bottom and about 8-3/4-inches from the bottom, using lathe chips taken across the entire wall at approximately the final machined dimensions. The carbon analyses are reported in Table I.

The following factors are known to affect carbon content in the thorium-uranium alloys:

- 1) Initial carbon content of charge materials
- 2) Holding time of molten alloy
- 3) Melt temperature
- 4) Efficiency of crucible coating in preventing metal attack.

Because the carbon content of only a portion of the thorium charge material (see section A.1.c) was known, the data on carbon pickup are necessarily based upon assumptions regarding the unanalyzed material. The initial carbon content of the thorium charge material averaged 600-800 ppm, and most of the castings contained 1200-1500 ppm carbon. The apparent carbon pickup is therefore in the range of 500-800 ppm. For the casting made entirely from remelt materials (TX-1382), an increase of only about 250 ppm carbon was indicated. In melt TX-1394, the very high carbon content (3060 ppm) resulted from the presence of stray graphite granules in the mold, as previously described. Casting TX-1414 had a somewhat higher carbon content than the other castings, for no known reason. For one casting (TX-1407), drill samples were analyzed from the inside, middle, and outside wall areas at bottom and top, both on the wall directly beneath the pouring stream and the opposite wall. No segregation of carbon was found in any of the areas sampled.

Uranium Homogeneity. Samples were analyzed for uranium content from chips taken in the same areas as for carbon content. The uranium analyses, reported in Table I, indicate good homogeneity in the castings.

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 II. 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 II, 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 ksi 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 III 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 II, ~~but no~~ ^{so} 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 ~~billet~~^{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. 3. The billet components were patterned after those used in the recent program on driver tubes for the HWCTR (NMI-7263).

Two sets of core preshapes, each set consisting of a front and a rear preshape, were designed for testing in the prototype billets. One set, Fig. 4, with the matching end seals in Fig. 5 was designed to give short core end tapers in the extruded tube. Because of the possibility of some thinning of the cladding with this preshape, the second set (Figs. 6 and 7) was designed to give more gradual core end tapers with a corresponding reduction of thinning of the cladding. The outside diameter of the core is 0.030-inch less than that of the end seals to compensate for differential thermal expansion during billet heating.

The Zircaloy-2 outer sleeve, Fig. 8, and inner sleeve, Fig. 9, were designed to give a cladding thickness of 31-1/2 mils in the as-extruded tube, thus allowing for the removal of 1-1/2 mils in final etching. A nose piece, Fig. 10, of zirconium rather than Zircaloy-2, was used in order to reduce the force required to initiate extrusion ("break-through pressure"). Copper cans were used with front weld plates perforated with three equally spaced 1/16-inch-diameter holes. These holes permitted slight oxidation of the copper and Zircaloy-2 during billet heating, reducing the degree of copper-Zircaloy surface interaction.

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. Three of the as-cast ingots were machined to the dimensions shown in Fig. 4 and one was machined as indicated in Fig. 6. The machined cores were inspected for surface defects and measured to ensure their conformance to dimensional specifications. Table I presents the data obtained for the prototype billet cores. 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 trichloroethylene, 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. Table V lists the preparation given to the billet component stock.

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 by scrubbing in an aqueous solution of trisodium phosphate, rinsing in water, and etching in a solution of 49 parts (by volume) concentrated HNO_3 , 2 parts concentrated HF , and 49 parts H_2O . The components were rinsed in successive baths of tap water, deionized water, and ethanol. Metal removal during etching was 1 to 2 mils on a diameter, with the workpiece submerged in the etchant ($46^\circ\text{--}52^\circ\text{C}$) for 40 seconds. Adequacy of metal removal was established by weighing each cladding component before etching and again after final rinsing. The etched components were inspected to ensure freedom from stains.

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. 3) 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 ferrocyanoide test for detection of tramp iron particles which could lead to surface depressions in the cladding during extrusion. The test consisted of swabbing the copper with a solution of 100 ml HCl and 900 ml of distilled water to which was added 50 gr $\text{K}_4\text{Fe}(\text{CN})_6 \cdot 3\text{H}_2\text{O}$. The appearance of a distinct blue spot denotes the presence of an iron particle. Following this test the cans were re-etched to ensure cleanliness and then stored in plastic bags with the freshly etched weld plates until needed for a billet assembly.

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 Hellarc 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 Hellarc 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 Dummy Billets

Three billets of nickel-free Zircaloy-2 canned in copper, and four billets consisting entirely of copper were prepared for preliminary extrusion trials.

The Zircaloy-2 used in the dummy billets was processed from a forging, as indicated in Table V. Two of the Zircaloy-2 billets (Nos. 0-1 and 0-2) were prepared with zirconium nose pieces similar to the nose pieces used for the composite billets, except neither the outside nor inside surfaces were recessed (i.e., the outside diameter was 6.951 inches for the rear 1-inch of length and the inside diameter was 1.981 inches for the entire 1-3/4-inch of length). The nose pieces were welded to the Zircaloy-2 around the outside periphery of their juncture. The third dummy billet (No. 0-3) was machined in one piece with the contour of the usual nose piece on the front of the billet. The Zircaloy-2 billets were washed in an aqueous solution of trisodium phosphate, rinsed in tap water, and canned in copper in the same manner as the composite billets.

The copper billets were machined in one piece from cast copper. Both the copper billets and the copper-canned Zircaloy-2 billets were coated with Aquadag before being packed for shipment.

4. 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 VI.

b. Preparation of Components

Preliminary evaluation of the prototype tubular elements indicated that both billet designs were satisfactory. However, shorter core and tapers were obtained with the short taper preshapes (Figs. 4 and 5) ^{and this was} 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. Description of the enriched cores used in the billets and notes on their final inspection are given in Table VII.

c. Assembly of Billets

Assembly of the enriched billets followed the procedures previously described for the prototype billets.

5. Shipment of Billets

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

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 KWOTR.

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 using the procedure in Appendix D. Data are presented in Table IX. 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 (Appendix B) and showed no evidence of cladding thinning. Data for tubes no. 1.1 and 1.2 are in Tables X and XI.

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. Core tip data for tubes No. 1.1 and 1.2 are in Tables XII and XIII.

Although all tubes passed the notch-fracture test at the Zircaloy-2 ^{cladding} to Zircaloy-2 end seals (specified in Appendix B), it was found that this type of test was too severe to determine Zircaloy-2 cladding to Th-U core bond strength. A stud test was formulated using 3/16-inch-diameter Zircaloy-2 studs welded to the cladding with circumferential and axial mill cuts through the cladding on the four sides of the stud. To control quality of the thorium-Zircaloy-2 bond, an average rupture stress for four studs of 60,000 psi was specified for indicating a satisfactory bond. A minimum rupture value of 25,000 psi for any one of the four studs was also specified. Eight stud tests made on uniform core sections of tube No. 1.1 ran from 90,000 psi to 108,000 psi, with an average of 99,000 psi. It was concluded that the Zircaloy-2 cladding to Th-U core bond was adequate for irradiation.

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 (Fig. 11), designed and fabricated by Moezik 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-235U tubes are in Table XIV.

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 XV 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). Shift and core end tapers, 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 (see Appendix C-2). 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-²³⁵U fuel assemblies were operated in the HWCTR under a test permit attached as Appendix E. Their histories are summarized below.

	<u>TMT 1-2</u>	<u>TMT 1-3</u>
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 exposure,* 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.

Sample irradiation data, tabulated by the ROTAN IBM program for fuel calculations, are presented in Figs. 12 through 19. The first two figures for each assembly, Figs. 12 and 13 for TMT 1-2 and Figs. 16 and 17 for TMT 1-3, present an early and the final listing of data,

as follows. The ROTAH code: (1) lists the date, input flow, and ΔT ; (2) shows the calculated element power; and (3) presents data representative of the conditions in each fuel assembly at the 21 layers under consideration. These 21 ROTAH layers are spaced equally on the fuel piece over a length corresponding to the same core weight or volume with uniform cross section, i.e., an equivalent core length. Thus the ROTAH column begins and ends not at the core extremities but in the tapered section of the core. Fig. 23 shows a schematic sketch of the layer positions. Layer 1 is 106 inches above the bottom of the fuel tube, intermediate layers are equally spaced every 4.9 inches, and layer 21 is 8 inches above the bottom. Data listed for each layer are for: (1) power shape, which are dimensionless numbers representing axial power distribution for the time interval of the data; (2) specific exposure; (3) channel temperatures; (4) fuel surface temperatures; (5) surface heat fluxes; (6) volumetric heat generation; and (7) specific power. To generate the above data, the ROTAH input data, as shown in Fig. 20, were used for the two fuel elements.

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 Fig. 14 for TMT 1-2 and Fig. 18 for TMT 1-3. For the hottest region of each assembly, all the data from the first exposure interval to the last are presented (Fig. 15 for TMT 1-2 and Fig. 19 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 in Fig. 21. 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. 21, column 5) 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. The equivalent time interval is derived in the following manner. All reactor power levels and the duration at those levels (within each real time interval) are recorded to permit accurate calculation of total reactor exposure within the real time interval. At a representative point (Fig. 21, column 2) within the real interval, reactor power and fuel element powers (flow and ΔT) are recorded. The reactor exposure (column 3) divided by that reactor power (column 4) yields the equivalent time interval (column 5) representative of all operation during the real time interval. Likewise, the flow- ΔT power of each fuel assembly (on each ROTAH sheet) for the equivalent interval yields data representative of its operation through the real time interval.

Power levels for the irradiation period of the Th-²³⁵U fuel assemblies are in Fig. 22. Shown are the daily power levels which have been averaged for the ROTAN 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 (see Appendix C-3). 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. 22) 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-²³⁵U assemblies is planned. Both test assemblies have been stored in the receiving basin for off-site fuel (RBOF) at the Savannah River Plant.

APPENDIX A

HWCTR TEST IRRADIATION PROPOSAL - 5

Prepared by: G. L. Tuer

Date: March 2, 1964

Objective: To determine irradiation stability of coextruded tubes of thorium metal of approximate dimensions and operating conditions predicted for prototype breeder reactor.

Type Element: Coextruded Zircaloy-clad Th-1.5 wt % U^{235} tubes having "SOT-6" external dimensions (i.e., 2.540-inch outside diameter and 1.830-inch inside diameter) with 0.030-inch cladding on each surface and a nominal total-core length of 108 inches.

Number of Assemblies: 2

Comments: The proposed irradiation represents the first attempt at SRP to irradiate thorium-uranium alloy under approximate power reactor conditions. The test is the first of a proposed series of about ten assemblies that will be irradiated to determine the effect of various fuel compositions on irradiation stability. These first two elements will contain no alloying additions; their performance will serve as a standard for comparison with materials used in later tests. Data from these tests will provide the basis for design of a fuel element for use in a prototype breeder reactor.

A. BACKGROUND

Du Pont has undertaken a program of design studies for both a reference and a prototype D_2O -moderated-and-cooled power and/or breeder reactor based on the Th- U^{233} fuel cycle. This program, which is described in DP-864 includes a continuing series of test irradiations in which materials, processing, and exposure variables will be evaluated, and in which data will be obtained for defining the operating limits and feasibility of future coextruded fuel tube designs.

No prior irradiation experience exists on Th-U alloys at SRP. Work at other sites has included fabrication development work at Nuclear Metals Incorporated, on Zircaloy-clad Th-U alloy tubes (NMI-7003), irradiation of Hanford-fabricated specimens of Th-U alloy in NaK-filled capsules at temperatures up to $400^{\circ}C$ in the BTR (HW-77052), and a series of NaK capsule irradiations at temperatures up to $1000^{\circ}C$ and with uranium contents in the Th-U alloy up to 31 wt % by ANL (ANL-5674).

A. BACKGROUND, Continued

Irradiation data from the above programs (see Fig. 1) suggest that, with thorium metal at temperatures of less than 550°C, exposures greater than 20,000 MWD/T (~2 atom % burnup) can be achieved with swelling no greater than 6 to 8 volume percent.

One of the objectives of the Th-U irradiation program is to develop at SRP and SRL a capability for fabricating and evaluating new power fuel elements as they may be required. In order to do this a cooperative fabrication program has been arranged with Nuclear Metals Incorporated in which NMI will do initial development work on extrusion characteristics of induction-melted Th-U alloys, will design and fabricate the extrusion billets; SRP will be responsible for extruding the billets on the 2750-ton press in Building 320-M and for finishing and evaluating the tubes that are made.

The two elements described in this test irradiation proposal are the first in a proposed series of about 6 to 10 test elements that will be identical except for core composition. Specific objectives of the proposed tests are:

- 1) Start irradiation of thorium tubes in FY-1964 at minimum cost.
- 2) Determine irradiation behavior of thorium-uranium alloy metal tubes for a tube size and operating conditions approximately equivalent to those in a power reactor.
- 3) Establish reference point for future materials tests planned in this series of irradiation.
- 4) Provide SRP and SRL with experience in fabrication and evaluation of coextruded tubes of Th-U alloy clad in Zircaloy.
- 5) Provide data for deciding on the suitability of the coextrusion process for the remote fabrication of fuel tubes when recycle thorium and U^{233} become available.

B. ELEMENT DESCRIPTION

Size

The two tubes proposed here for irradiation have the external dimensions of SOT-6 elements with the exception of length; the diametral dimensions are as follows:

	<u>Nominal, inch</u>	<u>Suggested Tolerance, inch</u>
Outside diameter	2.540	0.003
Inside diameter	1.830	0.003
Total wall thickness	0.355	0.006
Cladding thickness	0.030	0.003 Average over full core Minimum at end defects
Core thickness	0.023	
	0.295	0.008 Average

Tentative nominal dimensions of the finished tube are shown on STD4-5722 (Figure 2). Final detailed specification of dimensions and tolerances will be established on the basis of destructive evaluation of development tubes.

Length

The tubes will have a nominal over-all length of 118-1/8 inches, a nominal full-core length of 108 inches including both end defects, and a nominal over-all end-defect length at each tube end of 6 inches. The maximum and minimum total-core length (including end defects) are 112 and 104, respectively.

Numerous advantages would be gained by performing the irradiation test on tubular assemblies having 2 to 5 longitudinal segments; however, initial availability of time and funds did not permit the work which will be necessary to develop the segmented tube design; this development has therefore been postponed to subsequent irradiations.

Composition

The initial uranium concentration in the Th-U alloy has been chosen at $1.5 \pm .05$ wt % U²³⁵ added as uranium metal having an atom enrichment of 93.5 wt %. This concentration of U²³⁵ in the alloy was selected in order to approximate an optimum average specific power and maximum core temperature throughout the irradiation cycle. A higher initial U²³⁵ content would result in a more pronounced initial decrease in reactivity (the so-called "reactivity transient") while a lower composition would have provided a significant period of low power and temperature during the period U²³⁵ is building into the fuel. In Figure 3 is shown the predicted maximum fuel temperature vs exposure curve in an outer ring position of the HWCFR for a tube of the dimensions above.

The thorium-uranium will be irradiated as a binary alloy in the present test to minimize amount of alloy development work required. HAPC has favored the use of about 2 wt % zirconium as a ternary addition to the alloy claiming some fabricating, exposure, and corrosion advantages. The question of ternary additions will be raised at a suitable later point in the program.

Preirradiation Evaluation

Two prototype tubes will be coextruded that will contain Th-U alloy made up with natural uranium but containing the same total uranium content as the irradiation tubes. These tubes containing natural uranium will be destructively evaluated to determine end-defect shape (including taper, shift, and upset) so that billet design and/or end-plug

composition can be adjusted as required. Sections of the full core and of the end plug will be metallographically examined to determine cladding and core hardness, core structure, and amount and distribution of hydride in the cladding and end-plug Zircaloy.

Corrosion coupons will be saved from the end-plug material at each end of both the irradiation tubes and the tubes containing natural uranium cores.

A detailed evaluation test schedule will be prepared prior to time of actual evaluation work.

C. REQUESTED OPERATING CONDITIONS

In the test irradiations proposed here, it is desired that the maximum core temperature during irradiation be kept as constant as possible at a value of 510°C ; this temperature is a reasonable estimate of the maximum temperature that occurs in an operating power reactor of the present prototypical design (DDM-1); it furthermore represents an upper limit on the temperature that can be achieved with 180°C inlet coolant temperature and SOT-6 dimensions. It is realized that "level-temperature" operation will be impossible for a one- or two-tube insertion in HWCTR, but that a temperature transient similar to that in Figure 3 will occur; the effects of this transient should be minimized by moving the test assemblies from outer to inner test positions at an appropriate time during the irradiation.

It is requested that one tube be irradiated to 10,000 MWD/T and the second to 20,000 MWD/T. The predicted variation in specific power with exposure (Figure 3) indicated that an average monthly accumulation of exposure of about 1100 MWD/T will occur (assuming an average of 22 operating days per month). Thus a probable total exposure of 9 to 10 months and 18 to 20 months for the 10,000 and 20,000 MWD/T cases are indicated, respectively.

Assuming that the cooling water would have an entrance temperature of 180°C , the calculated initial temperature distribution over the length of the element is given in Figure 4. The variation of maximum core temperature and minimum burn-out safety factor with specific power is shown in Figure 5.

D. OPERATING DATA REQUIRED

It is desired to have thorough data on the irradiation testing of the two elements proposed in this test. This data should include a monthly summary of: 1) assembly power vs time, 2) flow and temperature monthly records for each of the two tubes, and 3) calculations of core temperature and surface temperature as a function of tube length; the calculations should be based on the best available computer code. A final data summary should be given for each tube as soon as possible after the conclusion of its irradiation period.

E. INTERIM EXAMINATION DATA DURING IRRADIATION PERIOD

It is recognized that handling of full length 180-pound irradiation tubes is a strong deterrent to extensive evaluation work on tubes during the course of an irradiation; however, a certain amount of dimensional checking is necessary particularly on the first tubes of a given type to be irradiated as in the present case. It is requested that: 1) both of the tubes be examined and reinserted at 4,000 - 6,000 MWD/T, 2) the 10,000 MWD/T tube be examined at the conclusion of its irradiation period, 3) the 20,000 MWD/T

tube be examined and reinserted after 14,000 - 16,000 MWD/T, and 4) that the same tube be examined at the end of the 20,000 MWD/T irradiation period. Following this plan, the first examination would be about September or October 1964 with new observations about every four months thereafter. The above nondestructive examinations, which presumably will be made in the receiving basin for offsite fuel, should include the usual visual examination measurement of outside and inside diameters over the length of the tube, and measurement of bow. The volume increase of a tube (swelling) is probably the most useful means of determining reactor performance in a nondestructive test.

F. POSTIRRADIATION DATA REQUIRED

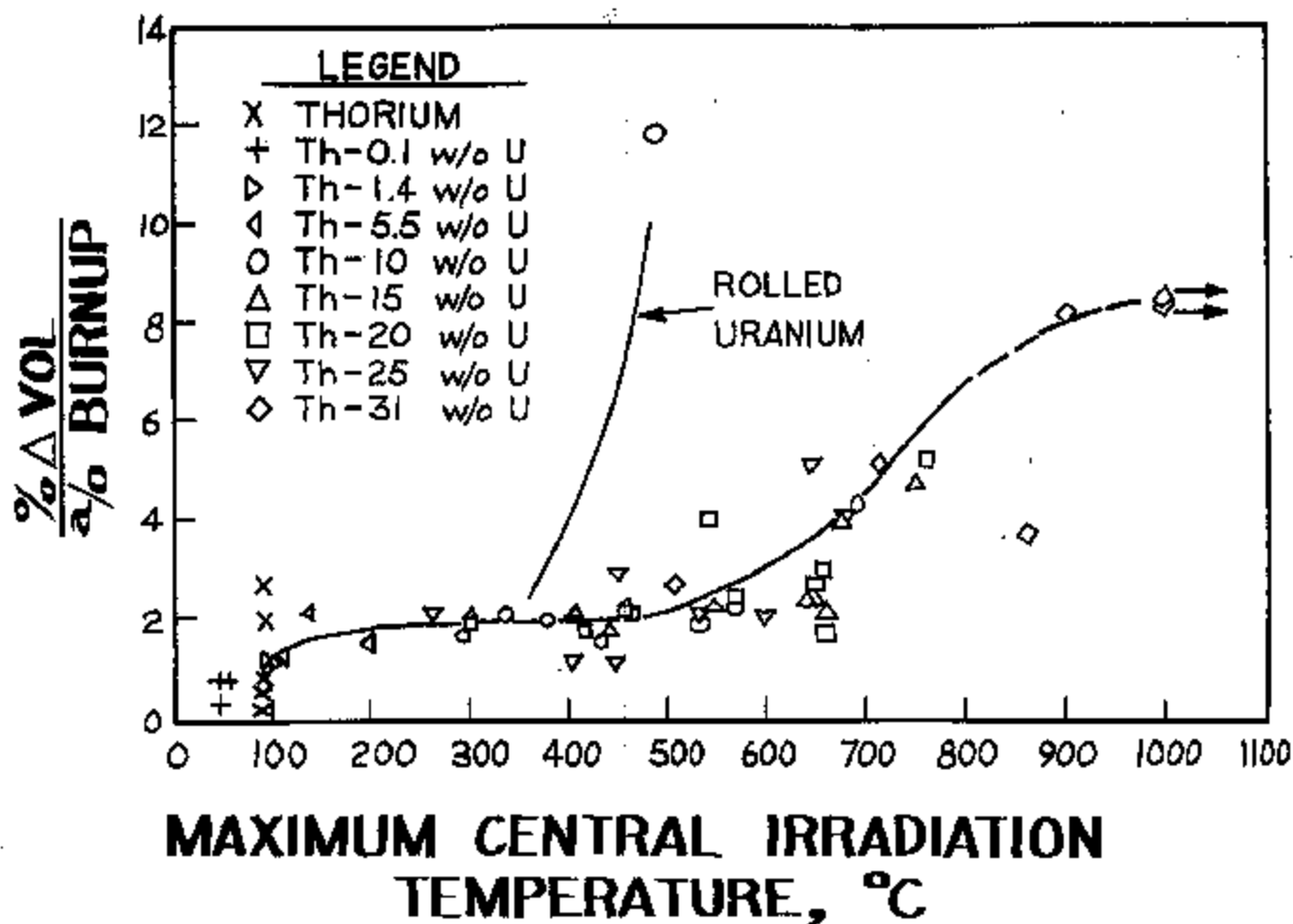
Destructive evaluation will be performed in the SRL High Level Cave facility. Samples for this evaluation should be prepared in the RBOF and shipped to SRL; these samples will include two or three 2-foot-long sections from each tube; a detailed sampling plan will be issued for each tube prior to the time it is to be sectioned. The sections will be examined in detail for cladding and core dimensional changes, for changes in the over-all tube density, and for changes in hardness and microstructure. Stud-weld tests will be made of the cladding-to-core bond layer.

G. SCHEDULE

The following is the approximate over-all schedule for the first Th-U alloy irradiations:

- | | | |
|--|---|---------------------------------------|
| 1) Initial fabrication development at NMI | - | December 2, 1963 to February 15 1964. |
| 2) Extrusion and evaluation of natural uranium mock-up tubes | - | March 15, 1964 to April 15, 1964 |
| 3) Extrusion and evaluation of enriched tubes | - | April 15, 1964 to May 15, 1964 |
| 4) Delivery of enriched tubes to HWCTR | - | May 15, 1964 |
| 5) Charge enriched tubes in HWCTR | - | June 1, 1964 |
| 6) Shift of tubes to inner ring - first examination in RBOF | - | September 1, 1964 to October 15, 1964 |
| 7) Removal of 10,000 MWD/T tube | - | April 1, 1965 |
| 8) Examination of second tube after 15,000 MWD/T | - | September 1, 1965 |
| 9) Removal of 20,000 MWD/T tube | - | February 1, 1966 |
| 10) Completion of examination of tubes from this test | - | June 1, 1966 |

QLT:ehj



(ORIGINAL DATA PRIMARILY FROM ANL-5674)

FIG. 1 IRRADIATION SWELLING OF THORIUM-URANIUM ALLOYS AS A FUNCTION OF TEMPERATURE

FIGURE 2

NOMINAL DESIGN OF THORIUM-URANIUM ALLOY TUBE

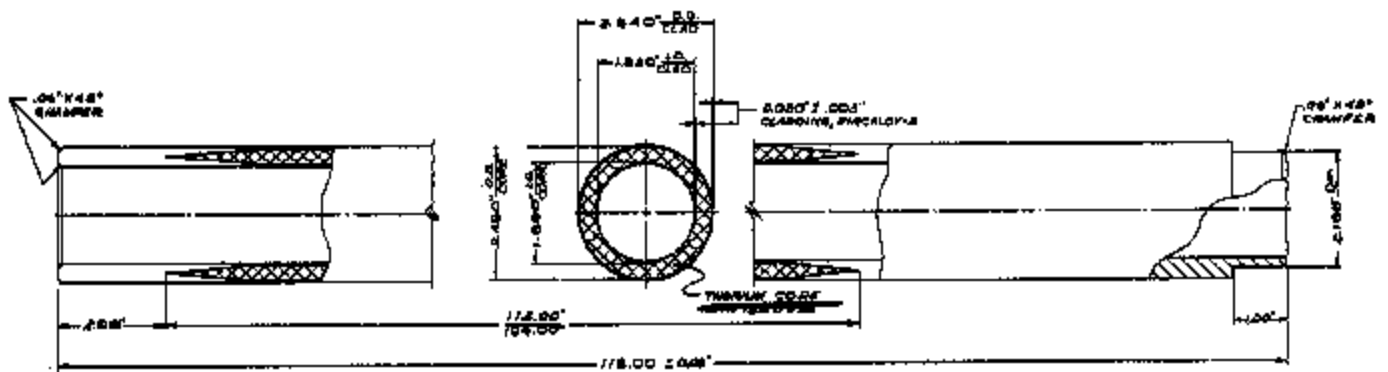


FIGURE 3. EFFECT OF IRRADIATION EXPOSURE ON MAXIMUM CORE TEMPERATURE AND SPECIFIC POWER

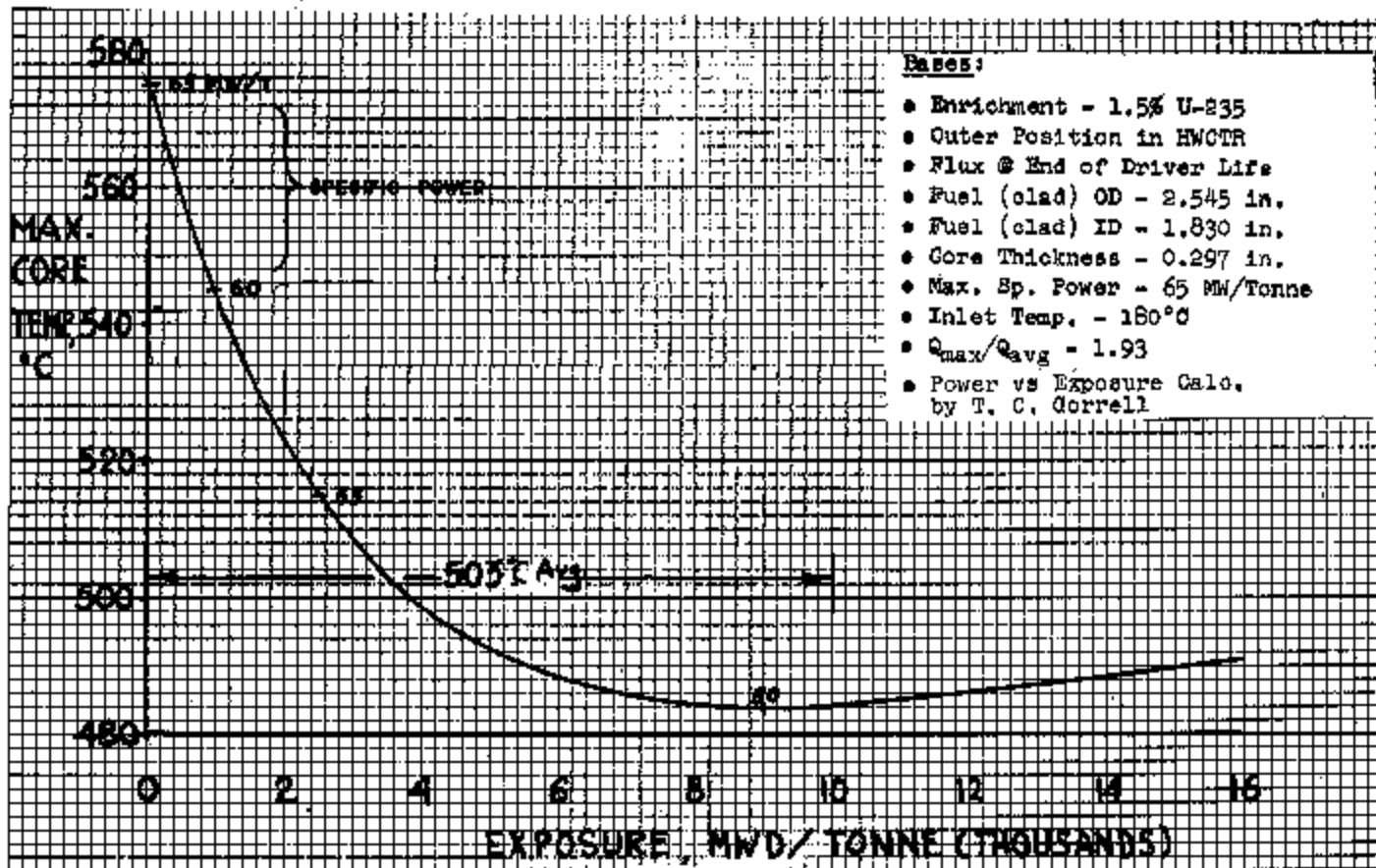


FIGURE 4. DISTRIBUTION OF SEVERAL REACTOR PARAMETERS OVER LENGTH OF TH-U ALLOY FUEL TUBE DURING EARLY STAGES OF EXPOSURE IN HWCTR

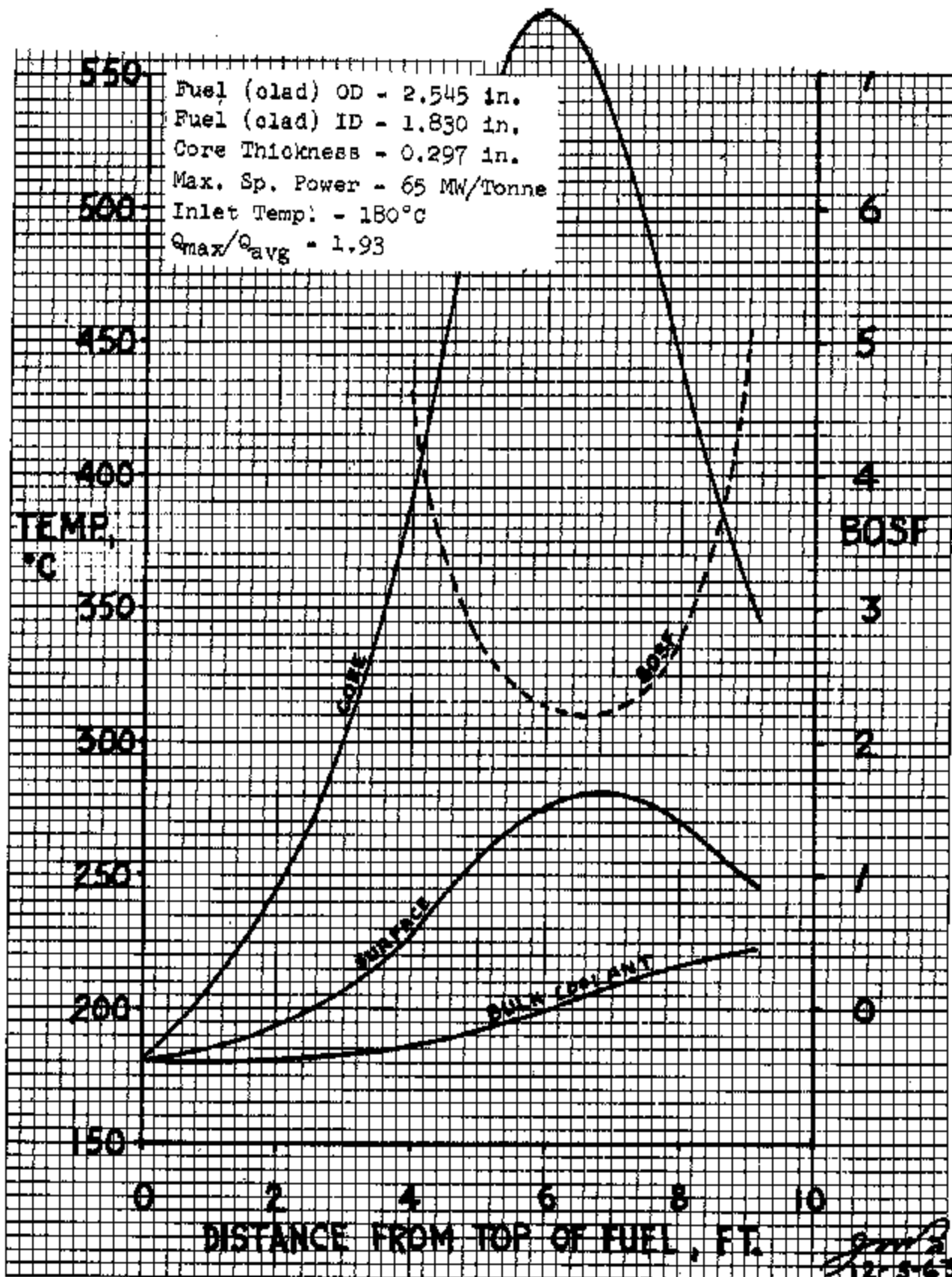
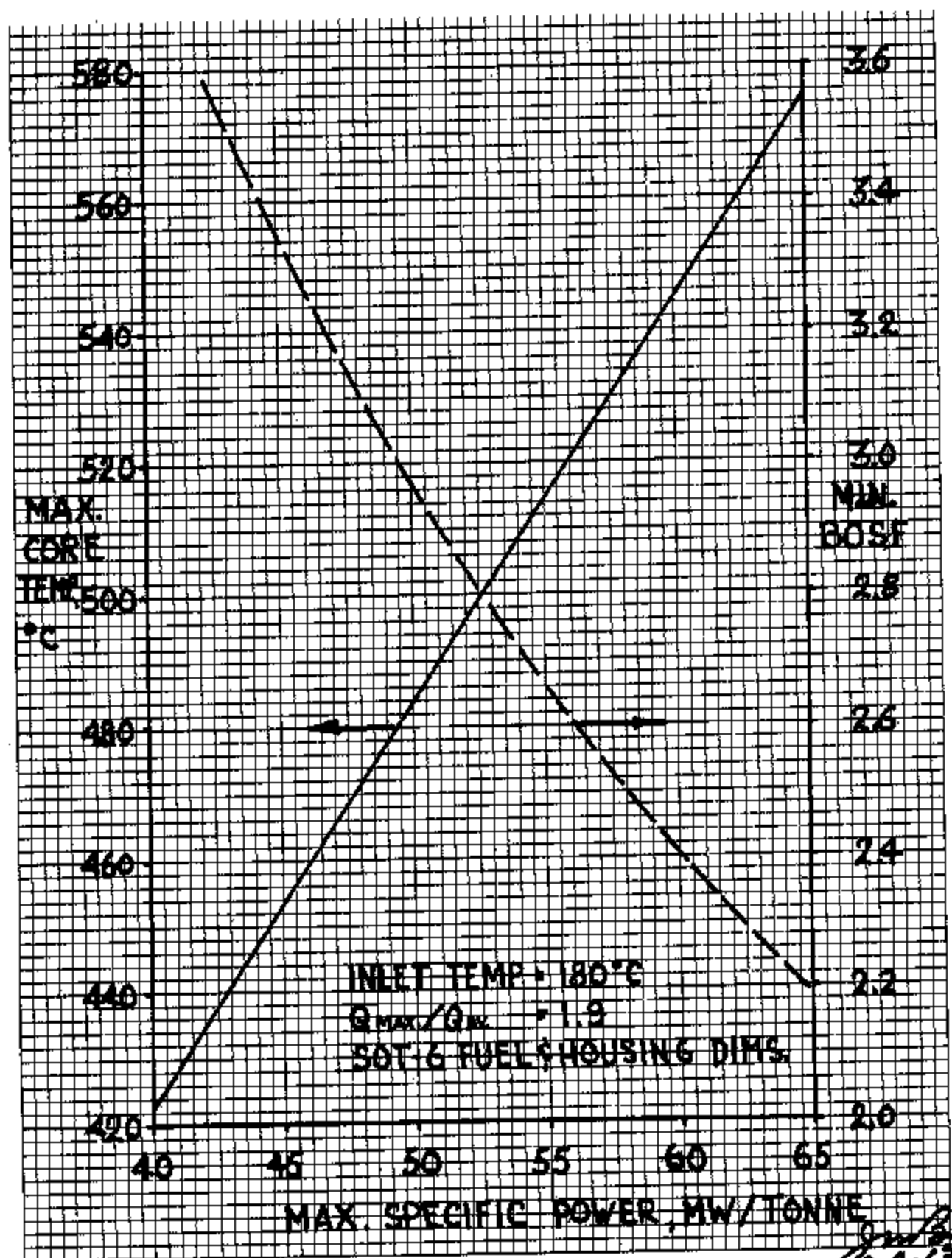


FIGURE 5. CALCULATED VARIATION OF MAXIMUM CORE TEMPERATURE AND MINIMUM BOSF WITH SPECIFIC POWER FOR Th-U ALLOY TUBES



APPENDIX B

July 1, 1964

DUPONT SPECIFICATION THORIUM-URANIUM ALLOY TUBES FOR HWCTR

This specification covers the technical requirements for the coextruded Zircaloy-clad Th-1.4 w/o U²³⁵ tubes for the HWCTR. Each tube consists of a core of thorium alloyed with a nominal concentration of 1.51 w/o uranium enriched to 93.5% in U²³⁵. The cores are fully clad with Zircaloy-2, including integral end seals.

A. DIMENSIONS

1. External Dimensions

The finished tubes shall comply with Du Pont drawing No. ST-MDX4-5722, Rev. 1 (attached) and the following:

a. Maximum Eccentricity

Eccentricity shall be defined as the difference between maximum and minimum wall thickness in any transverse ring section. Maximum eccentricity shall be 0.030 inch.

b. Bow

Bow shall be defined as the deviation of the external surface of the tube from a taut wire or string stretched between two points on the surface and parallel to the axis of the tube. Maximum bow over entire tube length: 3/32 inch. Maximum bow over any one-foot length: 0.010 inch.

c. Ovality

Ovality shall be defined as the difference between the maximum and minimum outside diameter on any transverse cross section. Maximum ovality shall be 0.015 inch.

2. Internal Dimensions

The finished tubes shall conform to the following requirements for internal dimensions:

a. Cladding Thickness (see Section D)

Average thickness
over uniform core: 0.030 ± 0.003 " (10%).
Minimum thickness: 0.023".

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b. Core Thickness (see Section D)

- (1) Core thickness, averaged over entire uniform core: 0.290 ± 0.009 " (3%).
- (2) Maximum core thickness including eccentricity: 0.310"

c. Core Length and Shape

- (1) Core length, tip-to-tip, as determined by radiography: 108 " nominal
 112 " maximum
 104 " minimum
- (2) Maximum taper, each end: 7" including shift, as determined by destructive examination of prototype tubes.

(Taper is defined as the distance from the core tip to the point where the core is 90% of the nominal thickness.)
- (3) Minimum end seal: 1" from core tip to point where cladding is machined.
- (4) Maximum shift of core tip (by radiography): $1\frac{1}{2}$ "

B. STARTING MATERIALS

1. Enriched Uranium

The enriched uranium used in the core preparation should be vacuum melted and produced from a cascade production of the diffusion isotope separation process. The isotopic composition of the enriched uranium shall be 93.5 + 0.5 w/o U^{235} . The uranium shall contain a maximum of 1.1 w/o U^{234} and a maximum of 5.9 w/o U^{238} .

Impurity levels should not exceed the limits specified in the table below:

<u>Element</u>	<u>ppm</u>	<u>Element</u>	<u>ppm</u>
Aluminum	50	Hydrogen	2
Boron	10	Iron	300
Cadmium	10	Magnesium	50
Carbon	500	Manganese	50
Cobalt	10	Nickel	100
Copper	50	Silicon	200

July 1, 1964

2. Zircaloy-2

Sleeve stock was procured from Harvey Aluminum, Inc. in the form of thick-wall tubing. Prior to extrusion the billet was beta heat treated and water quenched to remove preferred orientation induced by forging.

End seal stock was procured from Harvey Aluminum, Inc. in the form of forgings with a drilled center hole. Prior to final machining the forging was beta heat treated and water quenched.

The Zircaloy-2 starting material used in the manufacture of these tubes shall conform to "Du Pont Requirements for Zirconium and Zircaloy-2 Forgings", dated 7/31/63. The pertinent technical requirements of this document are listed below:

- a. Only reactor-grade zirconium shall be used.
- b. All ingots shall be made by the double vacuum arc-melting process.
- c. No recycle metal shall be used in fabricating the ingot unless otherwise indicated in the specific order. For the ingots prepared for these tubes, 15% recycle metal was used.
- d. The finished forged bars shall be ultrasonically inspected for defects. A Sperry Reflectroscope, Model UR-50 (or equivalent), shall be used. The equipment shall be operated with a 1-1/5-inch diameter, 2.25-megacycle crystal with oil couplant. Calibration shall be such that a 1/16-inch diameter hole drilled in a Zircaloy standard will show a 1-inch height indication on the oscilloscope. All the forgings shall be tested 100 percent, and any forging showing indication(s) equal to or greater than 1/16 inch shall be cause for rejection.
- e. The composition of the alloying elements in the forging shall conform to the requirements shown in the following table:

<u>Element</u>	<u>Composition (Weight percent)</u>
Tin	1.20 to 1.70
Iron	0.07 to 0.20
Chromium	0.05 to 0.15
Nickel	0.03 to 0.08
Zirconium	Remainder less impurities

The sum of the iron, chromium and nickel contents shall be within the range of 0.18 to 0.38 w/o.

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- f. The impurity levels of the finished forging shall not exceed the limits specified in the following table:

Element	Limit (ppm)	Element	Limit (ppm)
Aluminum	75	Manganese	50
Boron	0.5	Molybdenum	50
Cadmium	0.5	Nitrogen	80
Carbon	270	Oxygen	1000
Cobalt	20	Silicon	120
Copper	50	Sodium	20
Hafnium	200	Titanium	50
Hydrogen	25	Tungsten	50
Lead	130	Uranium (total)	3.5
Magnesium	20	Vanadium	50

- g. The hardness of the finished forgings shall not exceed 180 BHN using a 3000-kg load.

3. Thorium

The thorium used in the manufacture of these tubes is scrap metal resulting from a previous Du Pont program. This scrap came from unidentified ingots that were supposed to have conformed to "Du Pont Essential Material Specification No. 109". The pertinent technical requirements of this document are listed below.

- The ingots shall be made using thorium powder produced by calcium reduction of thorium oxide or thorium powder produced by fused-salt electro-refining of thorium metal scrap.
- The ingot charge may be either arc- or induction-melted.
- The charge for an induction-heated melt may contain 20% maximum solid metal scrap.
- The impurity levels of the finished ingots should not exceed the limits specified in the following table:

Element	ppm	Element	ppm
Aluminum	200	Iron	400
Beryllium	300	Magnesium	20
Boron	2	Manganese	50
Cadmium	2	Nickel	100
Calcium	100	Potassium	100
Carbon & nitrogen	600	Samarium	1
Chlorine	100	Silicon	100
Chromium	75	Sodium	100
Copper	50	Thorium oxide	1%*
Fluorine	100	Uranium	100
Gadolinium	1	Zinc	100
Hydrogen	10	Zirconium	100

*Thorium oxide content for scrap material used is between 1 and 2 percent.

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- e. The hardness of the finished ingot shall be in the range 50-60 BHN using a 500-kg load.

6. CORE CHEMISTRY

The core of each tube shall have a nominal composition of 1.4 w/o U²³⁵ in thorium added as uranium metal having a nominal atom enrichment in U²³⁵ of 93.5 w/o. The requirements for the concentration of U²³⁵ in the tubes are as follows:

1. Uranium

- a. The average wt % of total uranium in the core as determined by chemical analysis shall be 1.51 ± 0.05 (4%) (i.e., 1.45 to 1.57 wt %). A minimum of six distinct samples (3 top and 3 bottom) shall be taken in determining this average. If any individual sample falls outside the range of 1.36 to 1.66 wt % uranium two new samples shall be taken from the same region and analyzed. If either of the two check samples fall outside of the 1.36 to 1.66 wt % range, the ingot shall be rejected. All samples shall be included in the final average for a given ingot.
- b. The machined core weight prior to billet assembly shall be $39,600 \pm 400$ grams.
- c. Weight of U²³⁵ in any individual tube, as determined by billet core weight and analysis: 559 ± 28.0 grams ($\pm 5\%$).
- d. Weight of U²³⁵ in any one-foot length of uniform core section, where core thickness is within 2% of nominal as determined by billet analysis and calculated core cross section: 65.8 ± 5.2 grams ($\pm 8\%$). [$65.8 = 559 \div 102$ inches or $8\frac{1}{2}$ feet]
- e. Maximum U²³⁵ content in each square inch of wall segment as determined: (1) by billet core chemical analyses and core thickness measurements derived from tube-wall thickness measurements and calculated cladding thickness or (2) by gamma-scanning measurements of the finished tube: 0.873 grams (nominal plus 10%).

The actual maximum for the tubes to be irradiated will be determined to permit the calculation of hot-spot factors.

2. Carbon

The carbon content of the core should be within the range of 800 to 2500 ppm, to be determined by billet core analysis.

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D. CLADDING AND CORE THICKNESS

1. Average clad and core thickness over the uniform core shall be calculated from measured values of clad and core component thicknesses in the billet, extrusion reduction ratio and thickness of cladding removed during etching after extrusion.
2. Minimum cladding thickness at the end defects shall be determined by autoradiography of both the outer and inner surfaces of both tube ends. The autoradiographs shall extend from the end of the tube to a point at least 16 inches toward the tube center. Calibration of cladding thickness measurements shall be established by destructive evaluation of companion prototype tubes and confirmed by use of Zircaloy foil strips over the cladding.

E. BOND QUALITY

Acceptable bond quality shall be determined by the following tests.

1. Stud Test (prototype tubes only)

A minimum of 4 stud tests will be performed in the uniform core region of each prototype tube. The average bond rupture stress must be at least 60,000 psi with a minimum of 25,000 psi for any one stud.

2. Notch-Fracture Test

A ring section approximately $\frac{1}{4}$ -inch long shall be cropped from the end seal region of each end of each tube and subjected to a notch-fracture test. The ring section shall be prepared as shown in Figure 1. Fractures are rated according to the system described in Figure 2. Acceptable bond quality is indicated by a fracture rated either "good" or "excellent".

3. Ultrasonic Bond Test

Each tube shall be subjected to ultrasonic test for lack of bond between core and clad. A transmission type of test shall be used. The scanning sequence shall be such that the surfaces over the entire core region, including end tapers, are scanned.

The rejection level shall be set at a response equivalent to that produced by an unbonded area $\frac{1}{4}$ -inch diameter and parallel to the tube surface in a standard test specimen. The sensitivity of the equipment shall be adjusted so that this standard defect can be consistently detected.

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4. Bond Line Corrosion

The surfaces at both ends of all autoclaved tubes and ring sections (see Section F) shall be visually inspected. Any white or gray corrosion product at the clad-to-end seal bond line shall be cause for rejection.

5. Visual Inspection for Blisters

Blisters on either the inside or outside surfaces of the finished tubes shall be cause for rejection.

F. CORROSION RESISTANCE

1. Completed Tubes

Each tube in the final machined and bright-etched condition shall develop a lustrous black film with no white or gray corrosion product in excess of that shown on a standard specimen (selected from prototype tube sections or end sections from radiation tubes) after exposure to 24 hours in 650°F water followed by 24 hours exposure to 750°F steam at 1500 psi.

2. Tube Specimens

A ring section of the Zircaloy cladding and the Zircaloy end seal approximately $\frac{1}{2}$ -inch long shall be cropped from each end of each tube and subjected to a corrosion test. These test sections shall have no more metal removed from their surfaces prior to testing than will the finished tubes prior to autoclaving. This corrosion test shall consist of 3 days exposure to 750°F steam at 1500 psi. After test, all surfaces of the sample shall exhibit a lustrous black film with no white or gray corrosion product in excess of that shown on a standard specimen. This standard is to be selected from sections of prototype tubes. In addition, the sample shall have a weight gain of 17 ± 5 mg/dm².

G. SURFACE FINISH

Both the inside and the outside cylindrical surfaces of the tube should have a maximum surface roughness of 63 RMS in the longitudinal direction and 250 RMS in the circumferential direction.

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H. SURFACE DEFECTS

Requirements (a) through (e) below shall apply to the finished tubes; requirement (f) shall apply to the tubes after etching but prior to autoclaving. Notwithstanding any of the requirements below, the minimum clad thickness specification of 0.023" must be met. Visual inspection shall be used to determine compliance with these requirements. Borescope inspection shall be used on the inside surfaces prior to final etching.

- (a) All surfaces of the tubes shall be free of cracks.
- (b) The cylindrical surfaces of the tubes shall be free of laps or folds.
- (c) The cylindrical surfaces of the tubes over the core regions, including end tapers, shall be free of striations that are less than 0.010" wide and greater than 0.002" deep.
- (d) The cylindrical surfaces of the tubes over the core regions, exclusive of the end tapers, shall be free of handling or tool marks (e.g., scratches, gouges or scrape marks) greater than 0.005" in depth.
- (e) The cylindrical surfaces of the tubes shall be free of inclusions.
- (f) The cylindrical surfaces of the tubes over the core regions, exclusive of end tapers, shall be free of pits that are either black in color, greater than 0.004" deep, or do not show a lustrous rounded bottom.

I. IDENTIFICATION

Each tube shall be marked with a serial number, located in accordance with the applicable Du Pont drawing. This number shall be related to the complete set of fabrication and inspection records for that tube.

J. PACKAGING AND SHIPPING

When completed, each tube shall be packed in a container in such a way as to avoid damage to the tube during storage and shipping.

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K. REPORTS

A record of the fabrication history and inspection data shall be compiled for each tube. This record shall include the parameters used in the critical process steps, such as melting, casting, extrusion and all final inspection data including the following:

- (1) All final diameter readings.
- (2) Average core and clad thickness (including minimum clad).
- (3) Length of core.
- (4) Bow (amount and location).
- (5) Loading of U²³⁵.
- (6) Average loading of U²³⁵ per foot of uniform core.
- (7) Maximum U²³⁵ per square inch of wall segment.
- (8) Any rework required to meet requirements of Section H, "Surface Defects". Any proposed work shall be discussed with Du Pont prior to execution.
- (9) Autoradiographs and radiographs (or prints thereof).

A brief report shall be prepared containing the data noted above for each tube. This report will also include any deviations from this specification.

APPROVALS:

(Signed) P. H. Permar 6/16/64
Research Manager, Pile Materials Section

(Signed) E. C. Nelson 6/18/64
Research Manager, Pile Engineering Section

(Signed) L. M. Arnett 6/25/64
Supervisor, HWCTR Task Force

(Signed) W. B. DeLong 6/29/64
Director, Reactor Materials Section, AED

(Signed) D. F. Babcock
by R. R. Hood 6/25/64
Director, Reactor Engineering Sect., AED

SRN/jas

Attachments: Figure 1, Bond Test Sample Preparation
Figure 2, Bond Classification
Drawing ST-MDX4-5722, Rev. 1

FIGURE 1
BOND TEST SAMPLE PREPARATION

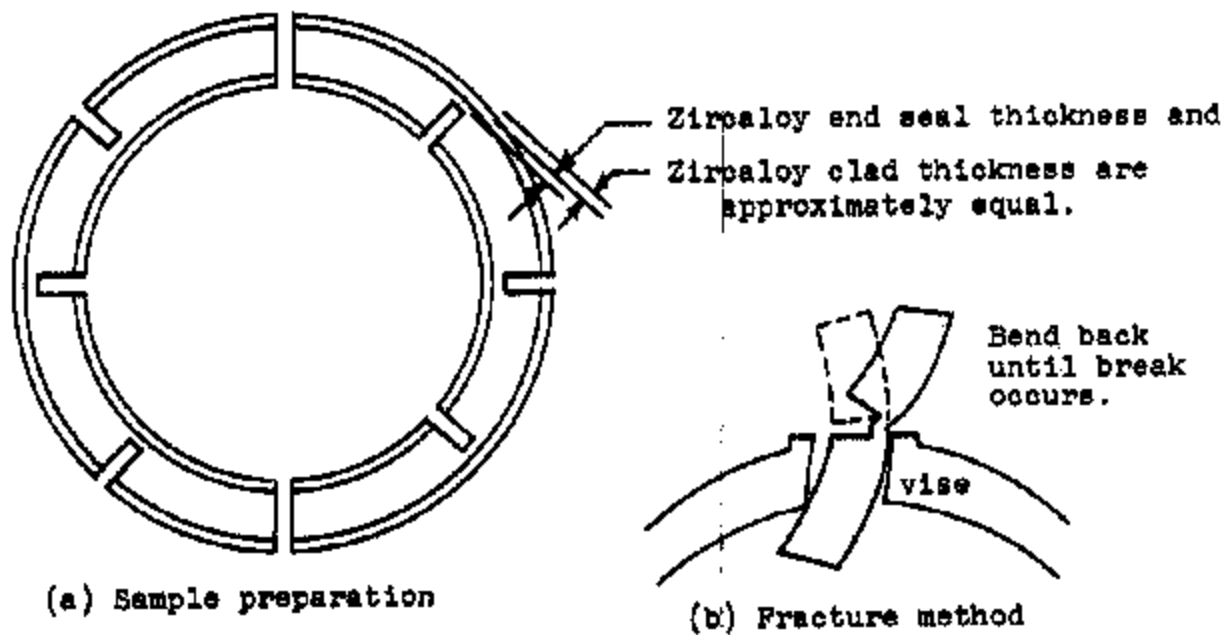
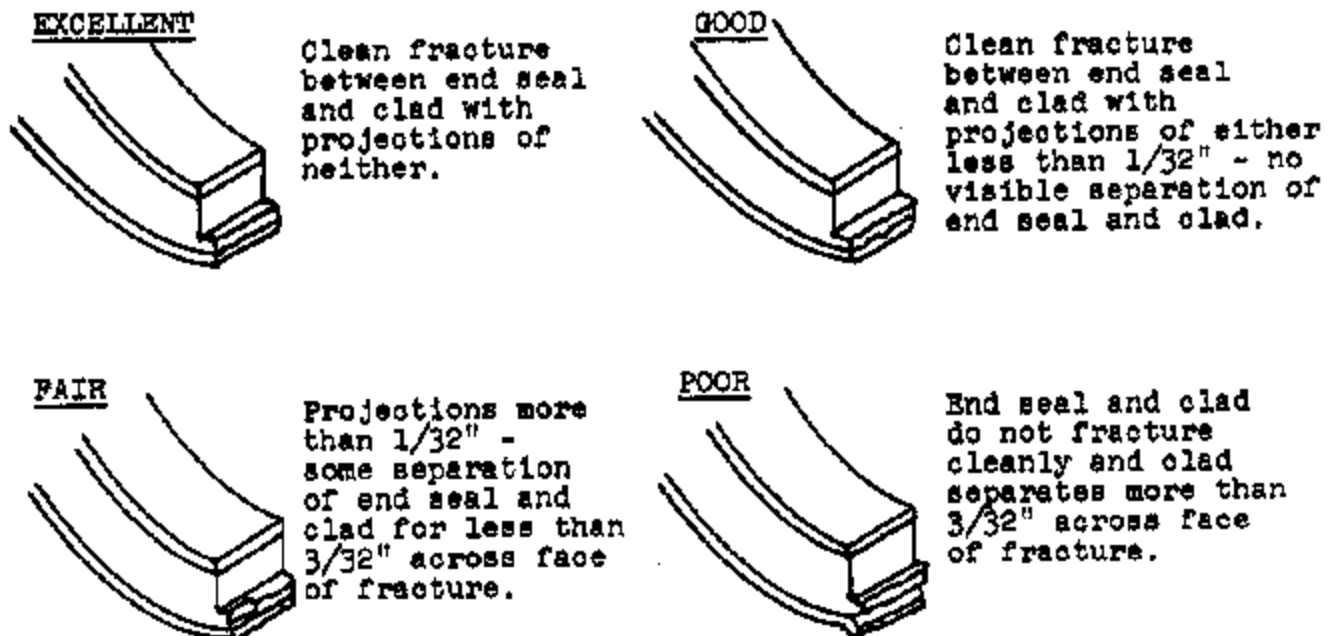


FIGURE 2
BOND CLASSIFICATION



APPENDIX C-1

TECHNICAL DIVISION
SAVANNAH RIVER LABORATORY

HWCTR TEST IRRADIATION DESCRIPTION-5

Assembly: Thorium Metal Tube (Thorium with 1.5 w/o U)

No. of Assemblies: 2 (TMT-1-2, TMT-1-3)

Target Irradiation Date: August 1964

Assembly Completion Date: July 29, 1964

Assembly Reference Dwg.: ST-MDX5-5837

Prepared by: A. F. Wright

Purpose of Irradiation: To determine the irradiation stability of coextruded tubes with thorium metal cores.

Description of Fuel Assembly

This assembly contains a ten foot long fuel tube (2.54" OD x 1.84" ID) in which the core is thorium - 1.5 w/o U (93% enriched) coextruded with 30 mils of Zircaloy cladding. The Zircaloy outer housing is an integrally ribbed tube (2.90" ID). The Zircaloy inner housing (1.42" OD x .030" wall) has four 60 mil thick full length external ribs welded to it by the electron beam welding process.

The fuel tube (Figure 2) will be extruded at SRP; however, N.M.I. will fabricate the billets. Based on the first extrusions, the probable dimensions for the irradiation fuel tubes will be 2.545" OD x 1.845" ID with 30 mils of cladding on both surfaces.

The Zircaloy outer housing will be fabricated from the driver-test type of Zircaloy housing by machining the as-extruded rib circle of 2.150" to 2.590" \pm .010". This machining procedure leaves a rib tip flat 80 mils wide.

The mechanical design is similar to the previously designed and tested SOT-6 and SOT-9. Minor changes were made to accommodate a single full length tube instead of a column of short fuel pieces; however, these were not sufficient to affect the flow distribution. The actual flow split will be determined at CMX and the flow will be orificed if necessary to match the SOT-6 so that the flow monitoring efficiency of the SOT-6 bottom fitting will apply to this assembly.

Listed below are the pertinent dimensions of this fuel assembly:

<u>Outer Housing</u>	<u>Inches</u>	<u>Fuel Tube</u>	<u>Inches</u>	<u>Inner Housing</u>	<u>Inches</u>
OD	2.96	Clad OD	2.545	R.C.	1.80
ID	2.90	Core OD	2.485	OD	1.42
R.C.	2.59	Core ID	1.905	ID	1.36
		Clad ID	1.845		

Uniform Core length, in. 87.5

Tip to tip core length, in. 109

Effective core length, in. 98

Prior to irradiation the assembly will be flow tested at reactor temperature, pressure, and flow at least thirty days. After the initial inspection, the flow test should continue for six months with periodic inspections.

Operating Characteristics

Throughout the irradiation the goal is to maintain the maximum central metal temperature in a range of 475°C to 500°C . To accomplish this the assembly power can be adjusted a limited amount, without affecting the reactor power, by moving it within the reactor or by using a stainless steel housing rather than the Zircaloy housing. The stainless steel housing will decrease the assembly power about 15% while moving the assembly from an outer to an inner position will increase the power about 10%.

Listed in Table I are the predicted operating characteristics. The conditions are nominal for operation in an outer position during the M-2 cycle with an average maximum central metal temperature of about 500°C . Future conditions cannot be predicted accurately because they depend on such factors as total exposure, Driver cycle (M-2, M-3 or O-1) position in the reactor, type of housing (Zircaloy or stainless steel) and length of any interim shutdown which would allow the Pa-233 to decay to U-233.

The stainless steel housing (Figure 3) to be supplied with each assembly is made from a tube (2.9" ID x .065" wall) and will have four ribs (.06" thick) welded to it by the electron beam welding process. The housings will be identical to the Zircaloy housings but they will differ in the fact that the top and bottom end fittings will be welded on to the stainless steel housing tube.

TABLE I
CALCULATED OPERATING CONDITIONS

	<u>Start of</u> <u>Cycle</u>	<u>Avg. for</u> <u>20,000 WD/G</u>
Reactor Pressure (PSIG)	1200	1200
Coolant Inlet Temperature (°C)	180	180-230
Maximum Specific Power (W/G)	58	58-45
Maximum Central Metal Temperature (°C)	510	~500
Maximum Surface Temperature (°C)	257	300
Maximum Heat Flux (pou/hr-ft ²)	4.46X10 ⁵	4.0X10 ⁵
Assembly Power (MW)	1.11	1.0
Maximum Flux/Average Flux	1.9	1.9

	<u>Outer</u>	<u>Inner</u>	<u>Axial</u>	<u>Total</u>
Heat split (%)	55.6	43.4	-	100
Flow split (%)	54.6	41.4	4.0	100
Channel ΔT (°C)	29.3	29.6	-	28.3
Channel flow (GPM)	82	62	6.0	150
Velocity (fps)	18.2	19.4	1.3	-
BOSF (with overall HSF of .65)	2.73	2.71	-	-

Special Handling Requirements

This assembly will not require any special tools for normal handling. The assembly components use the standard 1"-2"-3" top fittings. Initial assembly will be done by the Pile Engineering Division.

Should the stainless steel housing be required, the assembly can be sent to RBOF for changing the housing or it can be changed in the Spent Fuel Basin of HWCTR but not as conveniently.

The Zircaloy and stainless steel housings will have the standard identification numbers on the top and bottom fitting but will have either "Zircaloy" or "stainless" written directly below it.

Preirradiation Inspection

The following preirradiation data on the fuel tube will be collected by PED:

1. Outside diameters will be measured by means of continuous longitudinal scans at 0° , 45° , 90° , and 135° or micrometer measurements at 1" intervals.
2. Inside diameter will be measured at 1-inch intervals with a 2-contact mechanical gauge.
3. Length will be measured at 90° .
4. Photographs will be taken of the outside surface in the region of highest exposure.

Interim Examinations

Interim examination should be made at about 5000, 10,000 and 15,000 WD/G prior to the final examination at 20,000 WD/G. These examinations should be coordinated with scheduled shutdowns.

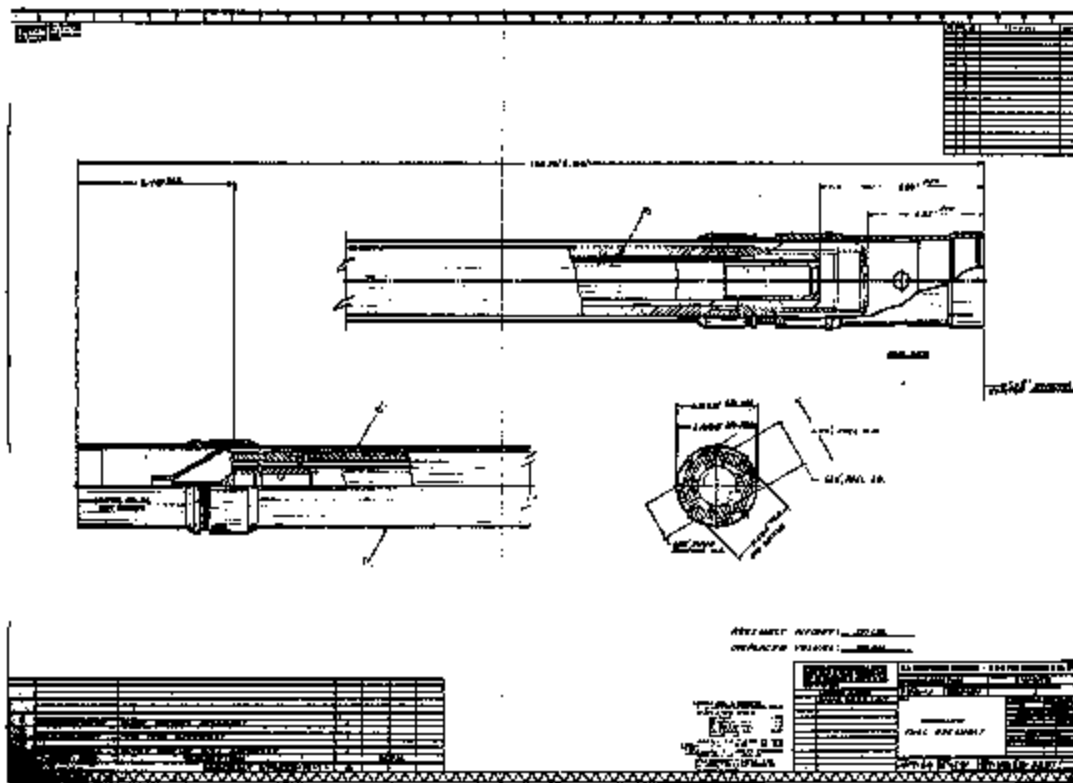


FIGURE 1

APPENDIX C-2

TECHNICAL DIVISION
SAVANNAH RIVER LABORATORY

HWCTR TEST IRRADIATION DESCRIPTION-5
ADDENDUM 1

ASSEMBLY NO: TMT-1-1

PURPOSE: Calibration and Long Term Flow Test

REACTOR: None - CMX Power Flow Loop

ASSEMBLY REFERENCE DRAWING: ST-MDX5-5837
Drawing Schedule #107

PREPARED BY: A. F. Wright *AFW*

The fuel in this assembly is a ten foot long coextruded tube (2.54" OD x 1.84" ID) containing a thorium - 1.5 w/o natural uranium core with 30 mils of Zircaloy-2 cladding. The outer housing is an integrally ribbed Zircaloy tube (2.90" ID) while the ribbed inner housing consists of a Zircaloy tube (1.424" OD x .03" wall) with four 60 mil thick external ribs welded to it by the electron beam welding process.

The assembly is a complete prototype except that natural uranium is used in place of enriched uranium in the core and 2 holes 1/16" diameter were drilled into the outer housing for pressure taps.

This assembly is identical to the SOT-6 and SOT-9 design and the flow split will be orificed as necessary to match the SOT-6 so that the flow monitoring efficiency results will also apply. By adapting an existing design, it was possible to reduce design time, prepare components quicker, and eliminate the need for a new monitoring efficiency test rig.

ASSEMBLY COMPONENTS

Housing - SRL #43 (originally machined to M-1 rib circle for initial checkout at HWCTR)

- Assembled length 132-3/8" (3/8" short of standard)
- Reference Drawing ST-MDX5-5835-A

Bottom Fitting Data

- Flow Sampler, ST-MDX4-5689
- Bottom Sleeve Drilling, ST-MDX4-5694-C, Rev. 5
(42 holes @.250" = 200" ΔP H₂O with 150 gpm D₂O at 200°C)

<u>Flow Data</u>	<u>Outer Annulus</u>	<u>Inner Annulus</u>	<u>Axial Channel</u>	<u>Total</u>
Flow (%)	55	40	5	100
Flow (GPM)	82.5	60	7.5	150
Velocity (fps)	18.1	19.5	1.6	-

FUEL - Assembly Drawing ST-MDX4-5831

- Fuel tube ST-MDX4-5722, Rev. 1
- PMD Extrusion #1-3 (front of extrusion is bottom of fuel tube)
- Overall length: 122-3/4"

Inner Housing - Assembly Drawing ST-MDX4-5828-A, Rev. 0

- Overall length = 121"

Loading Data

- Top of housing to top of fuel: 3-27/32"
- Top of housing top of inner housing: 5-17/32"

Loading Comments

- The components were loaded in the soap tank of the mockup room of 773-A to check the complete assembly. Then it was disassembled and the components were shipped to CMX.
- The fuel tube loaded under its own weight but was binding most of the time.
- The inner housing loaded under its own weight and could be rotated to seat on the orienting device.

AFW:js

TABLE I
ID MEASUREMENTS OF Th-²³⁵U ELEMENT NO. TMT 1-1

5/28/64

P.L.G. and T.A.D.

Distance from Top of Tube (Inches)	(Nominal ID = 1.830")			
	0°	45°	90°	135°
3	1.842	1.848	1.845	1.848
6	1.847	1.848	1.846	1.842
9	1.850	1.849	1.849	1.833
12	1.835	1.834	1.835	1.834
15	1.836	1.835	1.836	1.838
18	1.839	1.840	1.837	1.839
24	1.842	1.840	1.840	1.841
30	1.840	1.839	1.840	1.841
36	1.840	1.839	1.839	1.840
42	1.840	1.839	1.838	1.839
48	1.840	1.839	1.839	1.839
54	1.840	1.840	1.838	1.838
60	1.839	1.840	1.839	1.839
66	1.839	1.839	1.839	1.838
72	1.839	1.839	1.839	1.838
78	1.839	1.839	1.838	1.838
84	1.839	1.839	1.838	1.838
90	1.839	1.839	1.838	1.838
96	1.839	1.838	1.838	1.838
102	1.839	1.838	1.838	1.838
108	1.838	1.839	1.838	1.838

Note: Measurements made with 2-point Deep Hole Gage.

TABLE II
OD MEASUREMENTS OF Th-²³⁵U ELEMENT NO. TMT 1-1
5/28/65
P.L.C. and T.A.D.

Distance from Top of Tube (Inches)	(Nominal OD = 2.540")			
	0°	45°	90°	135°
3	2.540	2.539	2.541	2.537
6	2.536	2.535	2.536	2.537
9	2.544	2.544	2.543	2.543
12	2.542	2.544	2.544	2.542
15	2.541	2.542	2.542	2.542
18	2.542	2.541	2.542	2.542
24	2.543	2.541	2.542	2.542
30	2.542	2.541	2.541	2.540
36	2.540	2.540	2.541	2.541
42	2.540	2.540	2.541	2.541
48	2.540	2.540	2.541	2.541
54	2.540	2.539	2.540	2.541
60	2.540	2.539	2.541	2.541
66	2.539	2.539	2.540	2.541
72	2.540	2.539	2.541	2.540
78	2.540	2.539	2.541	2.541
84	2.541	2.540	2.541	2.542
90	2.540	2.541	2.541	2.541
96	2.540	2.540	2.541	2.541
102	2.541	2.540	2.544	2.542
108	2.546	2.541	2.547	2.545
111	2.547	2.543	2.547	2.546
114	2.546	2.544	2.548	2.547

TABLE III

ID MEASUREMENTS OF TMT 1-1 HOUSING TUBE NO. 43

5/20/64

W.R.H.

Distance from Top of Tube (Inches)	(Nominal Rib-to-Rib ID = 2.590")		
	0°	90°	Average
0	2.620	2.585	2.602
6	2.615	2.579	2.597
12	2.615	2.575	2.595
18	2.617	2.575	2.596
24	2.614	2.578	2.595
30	2.610	2.582	2.596
36	2.603	2.588	2.595
42	2.597	2.592	2.594
48	2.593	2.605	2.599
54	2.596	2.602	2.599
60	2.593	2.604	2.598
66	2.594	2.591	2.592
72	2.595	2.590	2.592
78	2.592	2.590	2.591
84	2.592	2.590	2.591
90	2.592	2.589	2.590
96	2.592	2.588	2.590
102	2.595	2.588	2.591
108	2.594	2.588	2.591
114	2.611	2.602	2.607
118	2.614	2.603	2.608

Note: Measurements made with 2-point Deep
Hole Gage.

TABLE IV

ID MEASUREMENTS OF TYP 1-1 HOUSING TUBE NO. 43

5/13/64

J.H.W. and J.L.H

Distance from Top of Tube (Inches)	(Nominal Housing Tube ID = 2.900")		
	0°	90°	Average
0	2.894	2.909	2.903
12	2.893	2.898	2.891
24	2.881	2.901	2.891
36	2.881	2.897	2.889
48	2.885	2.894	2.890
60	2.890	2.894	2.892
72	2.897	2.895	2.896
84	2.876	2.904	2.895
96	2.876	2.901	2.893
108	2.891	2.900	2.896

Note: Measurements made with 2-point Deep
Hole Gage.

APPENDIX C-3

TECHNICAL DIVISION
SAVANNAH RIVER LABORATORY

HWCTR TEST IRRADIATION DESCRIPTION-5
ADDENDUM 2

ASSEMBLY NUMBER: TMT-1-2 and TMT-1-3

PURPOSE: Irradiation - To determine the stability of coextruded thorium metal cores (T.P. #38)

REACTOR & POSITION: HWCTR- #40 (Outer Ring) - TMT-1-2
HWCTR- #37 (Outer Ring) - TMT-1-3

CHARGED TO REACTOR CYCLE: H-2.5, August 18, 1964

ASSEMBLY REFERENCE DRAWING: ST-MDX5-5837, Rev. 0
Drawing Schedule #107

PREPARED BY: A. F. Wright *afw*

The fuel in these assemblies is a ten foot long coextruded tube (2.54" OD x 1.84" ID) containing a thorium - 1.5 w/o uranium core (93% enriched) with 30 mils of Zircaloy-2 cladding. The outer housing is an integrally ribbed Zircaloy tube (2.90" ID) while the ribbed inner housing consists of a Zircaloy tube (1.424" OD x .03" wall) with four 60 mil thick external ribs welded to it by the electron beam welding process.

A stainless steel housing was supplied with each assembly and can be used in place of the Zircaloy housing to reduce the power by 15%. It is made from a stainless steel tube (2.9" ID x .065" wall) with four internal ribs (.06" thick) welded to it by the electron beam welding process. The housings will be identical to the Zircaloy housings but will have the end fitting welded to the stainless steel housing tube.

These assemblies are identical to the SOT-6 and SOT-9 design and the flow split matches the SOT-6 so that the flow monitoring efficiency results will also apply.

ASSEMBLY COMPONENTS

Housing - Zircaloy Housings

- a. Identified as "TMT-1-2 ZIRC" (D-81 letters left on at request of HWCTR Production.
- b. Identified as "TMT-1-3 ZIRC"
- c. Assembled length 132-3/4" (TMT-1-2 and TMT-1-3)
- d. Reference Drawing - ST-MDX5-5835-A, Rev. 0

- Stainless Steel Housings

- a. Identified as "TMT-1-2 SST"
- b. Identified as "TMT-1-3 SST"
- c. Both housings delivered to HWCTR on 8/18/64 and stored by HWCTR Production.
- d. Reference Drawing - ST-MDX5-5991, Rev. 0.

Bottom Fitting Data (TMT-1-2 and TMT-1-3)

- Flow Sampler, ST-MDX4-5689, Rev. 0
- Bottom Sleeve Drilling, ST-MDX4-5694-C, Rev. 3
(42 holes @ .250" = 200" AP H₂O with 150 gpm D₂O at 200°C)

Flow Data (TMT-1-2 and TMT-1-3)

<u>Flow Data</u>	<u>Outer Annulus</u>	<u>Inner Annulus</u>	<u>Axial Channel</u>	<u>Total</u>
Flow (%)	55	40	5	100
Flow (gpm)	82.5	60	7.5	150
Velocity (fps)	18.1	19.5	1.6	-

FUEL - Assembly Drawing ST-MDX4-5831, Rev. 0

- Fuel tube ST-MDX4-5722, Rev. 1
- Pre-irradiation dimensional data on file - to be published at completion of irradiation.

	Assembly		
	<u>TMT-1-2</u>	<u>TMT-1-3</u>	
Fuel Tube Length	122-3/4"	122-3/4"	Includes end fitting.
FMD Fuel Number	TMT-2-1	TMT-2-3	Stamped at top of extrusion.
Pre-Irrad. Avg. OD (Fuel)	2.538"	2.539"	From strip chart.
Pre-Irrad. Avg. ID (Fuel)	1.843"	1.841"	Deep hole gage.

INNER HOUSING - Assembly Drawing ST-MDX4-5828-A, Rev. 0

- Overall length = 121" (TMT-1-2 and TMT-1-3)

LOADING DATA

	<u>TMT-1-2</u>	<u>TMT-1-3</u>
- Top of housing to top of fuel	4-7/32"	4-1/4"
- Top of housing top of inner housing	5-15/16"	5-15/16"

LOADING COMMENTS (TMT-1-2 and TMT-1-3)

- The components were delivered to HWCTR and loaded in the presentation point by A. F. Wright and J. L. Harrelson.
- The fuel loaded under its own weight and could be rotated but with a slight bind.
- The inner housing loaded under its own weight and could be rotated to seat on the orienting device.

AFW/hhh

APPENDIX D

PROCEDURE FOR THORIUM-URANIUM EXTRUSION - BLDG. 320-M

GENERAL

Lubricants: Oildag for tool hoist
Oildag for container
Oildag for die
Alcohol-dag for mandrel, billet handling
devices, etc.

Temperatures: (These may be changed per instructions from
SRL only.)

Mandrel assembly	-	370 °C
Die	-	370 °C
Container	-	370 °C
Th-U billets	-	760 °C*
Cu billets	-	565 °C

Note: * Taken as the average of the permanently installed,
lower billet temperature indicator and the movable,
lower billet temperature indicator.

PRE-EXTRUSION OPERATIONS(1)

<u>Step</u>	<u>Description</u>
Prepare tooling.	Oxidize tooling, paint with Alcohol-dag, check and lube die and container.
Load tooling.	Record positions and orient properly.
Select billets.	Select billets to be extruded and designate into which furnace position they are to be loaded.
Load billets (2).	Load billets using designated furnace positions and orientation. Be sure carbon inserts are in place. Check quality of graphite. Nose of billet should be down; record billet positions.
Put thermocouples in place.	Install thermocouples for recorder.
Designate temperatures.	Designate the temperature at which all controls should be set both on furnaces and press tooling.

Notes: (1) Special tool and billet procedures must be followed when working with copper billets from 565 °C furnace.

(2) Billets preferably loaded into furnace at 760 °C 5 hours before extrusion. Billets to be loaded nose down with T-bar installed.

<u>Step</u>	<u>Description</u>
Set temperatures.	Set temperatures in accord with instructions.
Check temperatures.	Check temperatures of all furnaces, die and container. Container temperature will be checked with a surface pyrometer.
Prepare lubricant.	Mix Oildag and stir as required. At least two separate buckets will be required.
Set pressure-position recorder.	Set on 20" position prior to extrusion.
Set starting time.	Start extrusion sequence when conditions are satisfactory.
Start cooling table.	Start when tools are being unloaded from preheat furnace.

EXTRUSION OPERATIONS

Operators: A - press operator
 B - die head man
 C - handler
 D - handler
 E - die head assistant

<u>Operator</u>	<u>Step</u>	<u>Description</u>
A	Install ram extension.	Run ram into container to conserve heat.
B,E	Install runout tube in die slide.	
B	Lubricate die.	
A	Seat die.	
A,B	Position tube rack.	Place in slots in runout table graphite. Be sure hooks do not project above surface of graphite.
C	Attach clam shell to jib crane.	
A	Start timing with stopwatch.	

<u>Operator</u>	<u>Step</u>	<u>Description</u>
C	Turn off blower.	Outgassing furnace.
C	Open furnace door.	Outgassing furnace.
D	Position cart.	Use care to match rails accurately.
D	Pull out tool rack.	Be sure dolly does not jump track.
C	Pick up tools.	Attach clam shell to mandrel dummy block assembly, lock and raise using job crane. Note orientation of tools.
C	Lower tools to cart.	Technical personnel will record tool numbers. Also record tool temperatures with contact pyrometer.
D	Detach clam shell.	Unhook clam shell from jib crane.
D	Replace tool dolly into furnace.	Remove empty tool rack from tool dolly.
C	Move cart to mono-rail.	
D	Remove clam shell from tools.	
D	Attach clam shell to left side of mono-rail hoist.	
C	Upend tools.	Stand mandrel and cutoff block assembly on end, using dummy block as base.
C	Paint mandrel.	Stir lubricant (Oildag) and then thoroughly paint tooling. Let stand for 30 seconds.
D	Swab container.	Using long-handled swab, dip into Oildag lube and run through container twice. Note: This is signal to start billet loading sequence.
C	Horizontalize tools.	

<u>Operator</u>	<u>Step</u>	<u>Description</u>
C,D	Pick up tools.	Attach clam shell to mandrel; lock into place. Tools in proper orientation.
C,D	Position tools.	Use monorail hoist to raise tools and position over left-hand tie rod.
E	Position billet hoist.	Position monorail hoist over billet preheat furnace. Do prior to container swabbing.
B	Open furnace doors.	SRL will check temperatures (before opening doors).
B	Raise furnace lid.	Remove lid from designated (well).
B	Attach hook.	Insert hook into billet lifter.
E	Pick up billet.	
B	Close furnace doors.	
B,E	Move billet to loader.	
A	Replace lid and close furnace.	
A	Raise billet loader.	Raise loader to <u>top cross</u> position and hold.
E	Lower billet.	
B	Guide and horizontalize billet.	Using horizontalizer, hook the bottom of the billet lifter, guiding billet onto billet loader(1), simultaneously horizontalizing onto loader. "B" man crosses from right to left side of press.
B	Remove billet lifter (T-bar).	Toward left side of press.
E	Remove platform.	Pick up platform on right side of press.

Note: (1) Front of billet pointing toward left side of press.

<u>Operator</u>	<u>Step</u>	<u>Description</u>
C,D	Remove platform.	Remove platform on left side of press.
A	Raise billet loader.	Raise loader to <u>full up</u> position (from top cross position).
A	Load billet.	Move ram forward to push billet into container.
A	Return ram and raise loader.	Raise loader to full up position.
B	Put platform back in place on left side of press.	
C	Lower tools.	Lower tools onto billet loader.
B	Guide tools.	When tools rest on loader, unlock clam shell.
B	Remove left platform.	
A	Load tools.	Move ram forward to insert mandrel assembly into container.
D	Move clam shell.	Take clam shell back to preheat furnace.
A	Extrude.	Extrude at 12 inches/minute.
B	Mark 0° position on tube.	Mark 0° position on tube with file as it exits from die.
B	Break tube loose from mandrel.	Break tube loose from die and out of guide tube. If guide tube has come out, break from tube.
E	Raise tube rack.	Raise only enough to clear runout blocks and cooling rollers.
B,C	Guide tube rack.	Keep rack from tipping and guide hooks between rollers.
E	Lower tube rack.	Rest tube on rotating straightening rollers.
B,C	Disengage tube rack.	Take care not to knock tube off rollers. Place tube rack on floor alongside of runout table.
A	Move die from cavity.	Lift runout table; move die slide out.

<u>Operator</u>	<u>Step</u>	<u>Description</u>
D	Place board in die cavity.	Place flush with container face.
A	Clear container	Advance ram to push mandrel assembly into cavity.
B	Clear die cavity.	Remove tooling from cavity and place to one side.
D	Remove board.	
B	Clean die.	Check for cracks and chips. Use steel wool and fine emery but only as absolutely necessary to remove copper pickup.

POST-EXTRUSION OPERATIONS

<u>Step</u>	<u>Description</u>
Check die.	Check for damage and copper pickup. Change die if required (check with supervision) and relube.
Check container.	Check for cleanliness. Clean out and relubricate as necessary.
Obtain data.	Check post-extrusion temperatures, etc.; mark or remove sections of interest in pressure-position and temperature charts.
Clean up area.	
Disassemble tools.	When mandrel assembly has cooled to below 260°C, remove copper cutoff block.
Reassemble and reposition tools.	Container, die head, monorails, tube runout rack, etc.
Prepare for next extrusion.	Check over tools and billets to make sure everything is ready.
Move tubes to SRI.	Use carryall truck with tube racks on top.
Move portable thermocouple.	Put in place within next billet to be extruded.

APPENDIX E

HWCTR TEST PERMIT IRRADIATION OF THORIUM METAL TUBES (TMT-1 SERIES)

SUMMARY

This Test Permit authorizes irradiation of thorium metal tubes of the TMT-1 series in standard lattice positions of the HWCTR. Each test assembly contains a single full-length tube of thorium metal alloyed with 1.4% U-235 and coextruded with Zircaloy cladding on each surface. The fuel is designed to operate at an exposure-averaged maximum core temperature of about 500°C, to a maximum exposure of 20,000 watt-days/gram Th.

A summary of fuel dimensions and expected initial operating characteristics follows:

Clad fuel outer diameter, inches	2.545
Core thickness, inch	0.290
Nominal max specific power, watts/g Th	62
Nominal max core temperature, °C	500
Nominal max surface heat flux, pou/(hr)(ft ²)	455,000
Nominal max surface temperature, °C	266
Minimum BCSF	2.1
Minimum channel outlet subcooling, °C	62
Nominal max exposure, watt-days/g Th	20,000
Approximate irradiation time at full power, days	350

DISCUSSION

The purpose of these tests is to determine the behavior of thorium metal cores coextruded with Zircaloy cladding when irradiated at temperatures and to exposures required of fuel in the prototype breeder reactor.

FUEL ELEMENTS

The TMT-1 fuel cores are thorium metal alloyed with 93.5% enriched uranium to provide a core enrichment of 1.4% U-235. No other alloying metals are added. Performance of these cores will be a basis for comparing the performance with alloyed cores in later tests.

The cores are coextruded with Zircaloy cladding to form a tubular element of the following nominal dimensions:

Clad outside diameter, inches	2.545
Clad inside diameter, inches	1.845
Outer clad thickness, inch	0.030
Inner clad thickness, inch	0.030
Core thickness, inch	0.290
Core length tip-to-tip, inches	109
Uniform core length, inches	87.5
Equivalent uniform core length, inches	98
Mass of thorium in core, lb	81.5

The fuel tube is illustrated in Figure 1.

FUEL ASSEMBLY

The single fuel tube is contained in an outer housing tube of either Zircaloy or stainless steel. Use of the alternate housings is discussed in the following section. An inner housing tube of Zircaloy defines an inner surface coolant annulus. The Zircaloy outer housing has four integrally extruded ribs which provide a nominal rib-to-fuel clearance of 0.045 inch on the diameter, and have flat tips 0.080 inch wide. The stainless steel outer housing has four internal ribs of stainless steel attached by electron beam welding. These provide similar clearance but have flat tips 0.060 inch wide. The Zircaloy inner housing has four 0.060-inch-thick ribs electron beam welded to its outer surface. These provide a nominal clearance of 0.045 inch on the diameter.

Nominal assembly diameters are summarized below:

Outer housing outer diameter, inches	2.960 (Zr) 3.030 (S/S)
Outer housing inner diameter, inches	2.900 (Zr & S/S)
Outer housing rib circle, inches	2.590
Fuel clad outer diameter, inches	2.545
Fuel clad inner diameter, inches	1.845
Inner housing rib circle, inches	1.800
Inner housing outer diameter, inches	1.420
Inner housing inner diameter, inches	1.360

The assembly bottom end fitting is similar to that developed for the SOT-6 and SOT-9 assemblies. A prototype assembly, TMT-1-1 (Appendix C-2), was calibrated at CMX for total flow and flow split.

The prototype assembly will have been flow-endurance tested, under flow and temperature conditions similar to those expected in the reactor for at least 30 days prior to initiation of the irradiations. Irradiations will begin only if satisfactory flow test performance is indicated. The flow test will then continue in parallel with the irradiation, with periodic inspections to anticipate any potential long-term damage to the irradiation assemblies.

OPERATING CHARACTERISTICS

Estimated operating characteristics for the TMT-1 assemblies at the start of their irradiation are given in Table Ia. The maximum specific power of 62 watts/gram Th is based on a maximum thermal flux of 1.5×10^{14} n/cm²-sec. This is the estimated flux available in the outer test ring during the H-2.4 test cycle, with the moderator at 200°C.

The thorium fuel power is expected to vary more with exposure and irradiation history than any element previously irradiated in the HWCTR. Two effects cause this; one is a continuing long-term effect of burnup, and the second is a shorter-term effect due to isotope decay during interim shutdown periods.

At low exposure, the power of the element is governed by the U-235 enrichment. With long exposure, the build-in of U-233 becomes more important and after about 10,000 watt-days/gram Th an equilibrium U-233 level is reached so that power is then largely independent of the initial U-235 content. At this time, maximum specific power at constant flux would have decreased to about 50 watts/gram Th and maximum core temperature would be down from 500 to about 440°C. To compensate partially for this loss, the assembly may be moved to an inner test ring position to take advantage of an approximately 10% greater flux for a similar increase in power.

Complicating this long-term effect, however, is the effect of increased U-233 build-in during periods of shutdown after significant exposures. The U-233 concentration can be significantly higher at the end of a shutdown period than at the beginning. Thus, power in the element can be higher in startup following an outage than prior to the outage. Following the re-startup, U-233 concentration and power will decay somewhat but a new, higher, power

will result. Therefore, depending on its irradiation history, it is expected that during the latter part of its exposure, the power of a TMT-1 element may be greater than its earlier power and may limit the reactor power by minimum BOSF. To minimize this effect, the TMT-1 fuel may be installed in the stainless steel housings provided for the latter part of their exposure. This would attenuate thermal flux and reduce element power.

The operating characteristics of a TMT-1 assembly under such conditions are shown in Table Ib. Because the assembly is expected to be in the reactor for two years or more, these conditions are shown relative to operation with the O-1 drivers at a 250°C moderator temperature. It is also assumed that the reactor pressure will be 1400 psig at this time.

BURNOUT SAFETY FACTOR AND MINIMUM SUBCOOLING

Both the inner and outer coolant channels are annular. The correlation given below is used to estimate the nominal burnout heat flux for the predicted conditions and will also be used to estimate the BOHF during operation:

$$\phi_{BO} = 257,000 (1 + 0.04 K_V V)(1 + 0.03 T_s)$$

ϕ_{BO} = nominal burnout heat flux, pcw/(hr)(ft²)

V = nominal coolant velocity, ft/sec

K_V = over-all hot channel factor on velocity,
from Table II

T_s = minimum (using K_t from Table II x nominal ΔT)
subcooling at point of maximum heat flux, °C

Burnout safety factor (BOSF) for a given channel is computed as follows:

$$BOSF = \frac{\phi_{BO}}{\phi_{MN} K_q}$$

ϕ_{MN} = maximum nominal heat flux, pcw/(hr)(ft²)

K_q = over-all hot spot factor on heat flux, Table II

The operating minimum limit on BOSF is 1.8.

Minimum effluent subcooling is computed as follows:

$$\Delta T_{SC} = T_{Sat} - (\Delta T_M \times R \times K_t + T_{In})$$

T_{Sat} = saturation temperature at channel effluent, °C

ΔT_M = measured assembly coolant ΔT , °C

R = outer channel nominal $\Delta T / \Delta T_M$

K_t = hot channel factor on temperature for outer channel
(from Table II)

T_{In} = reactor inlet D_2O temperature, °C

The operating minimum limit on subcooling is 20°C.

Hot spot and hot channel factors to be used in calculating local heat flux, bulk rise, and coolant velocity are summarized in Table II. Effects accounting for each factor follow:

1. Circumferential Neutron Flux Variation

Measurements in the PDP have shown the variation in neutron flux around the circumference of a fuel tube not adjacent to a control rod to be ±5%. With banked rod operation, the region of maximum heat flux is below the rod tips, so $K_Q = 1.05$. Circumferential flux variation adjacent to rods could be as great as ±10%. Both TMT-1 coolant channels are ribbed so that discrete subchannels can form in which the enthalpy rise is as much as 10% above nominal in the upper part of the assembly adjacent to partially inserted rods. Therefore, $K_t = 1.10$.

2. Axial Power Shape

Because of uncertainties in calculation of the axial power shape, it is estimated that the peak heat flux could be as much as 3% greater than nominal. Therefore, $K_Q = 1.03$.

3. Core Thickness Variation

Variation in thickness of the core is no greater than ±0.015 inch. The nominal core thickness is 0.290 inch; therefore, local heat generation could be as much as 5% greater than nominal. Thus, $K_Q = K_t = 1.05$.

4. Fuel (U-235) Segregation

The thorium core is alloyed to give 1.4 wt % U-235. It is estimated that areas of significant size could have concentrations as large as 10% (relative) greater than this. Therefore, $K_q = 1.10$.

5. Heat Split Uncertainty

A 2% allowance is made for uncertainty in the calculated heat split between the inner and outer surfaces. Thus, $K_q = K_t = 1.02$.

6. Flow Split Uncertainty

The flow split was measured in the prototype assembly using H_2O at $30^\circ C$. It is estimated that in extrapolating to reactor conditions the flow split could be in error enough to produce flow 2% less than nominal in either channel. Therefore, $K_t = 1.02$ and $K_v = 0.98$.

7. Nonbonds

The minimum dimension of nonbond areas detectable in the TMT-1 tubes is about $1/16$ inch. Nonbond streaks of this width would cause local increases in heat flux of about 4%. This width of possible nonbonds, $1/16$ inch, is greater than the previously assumed $1/32$ inch for uranium elements extruded at NMI. However, the thick core of the TMT-1 element and the better conductivity of thorium metal tend to reduce the expected increase in heat flux. Therefore, $K_q = 1.04$.

8. Rib Contact

Contact of a spacing rib with a fuel surface tends to insulate the surface under the rib. This shifts the core temperature profile and causes an effective increase in surface heat flux adjacent to the rib and also in line with the rib on the opposite fuel surface. The heat flux increase is directly related to the rib contact thickness and inversely related to the conductance of the core and cladding. High thermal conductivity of the thorium core tends to minimize the effect. Rib tip widths are 0.060 inch for the inner housing and the stainless steel outer housing, and 0.080 inch for the Zircaloy outer housing. The inner and outer housings are mechanically oriented so that ribs cannot be "back-to-back". Relationships have been developed which indicate that the wider rib will effectively increase the heat flux.

adjacent to, and opposite it, by about 5%. The narrower rib will cause increases of about 4%. Analogy with previous calculations of temperature redistribution in a metal core resulting from a nonbond indicates that the increase adjacent to the rib will actually be somewhat greater than that opposite. Therefore with the Zircaloy outer housing, K_q for the outer surface is 1.06 and K_q for the inner surface is 1.05. With the stainless steel outer housing, K_q for both surfaces is 1.05.

9. Eccentricity

Eccentricity of the fuel tube relative to the housings can produce low flow in channels formed by the fuel contacting two of the four ribs on either housing. Enthalpy rise in such a subchannel in the outer annulus could be as much as 20% greater than normal and velocity could be 16% below normal. Therefore, $K_t = 1.26$ and $K_v = 0.84$. Similarly for the inner annulus $K_t = 1.20$ and $K_v = 0.87$.

10. Temperature Monitoring

Measured ΔT for the assembly can be in error from three causes; (1) poor sampling in end fitting, (2) thermocouple error, and (3) readout error. With nearly equal channel ΔT 's, the first cause will produce error no greater than $\pm 1\%$. Zero corrections are used with thermocouples and the maximum error in these is estimated to be $\pm 0.2^\circ\text{C}$. Recorder error is no greater than $\pm 0.5^\circ\text{C}$. This sum of 0.7°C is about 2% of the nominal ΔT . Therefore, $K_q = K_t = 1.03$.

11. Flow Monitoring

The variation in indicated flow with random angular orientation of the end fitting is about $\pm 1\%$. Experience indicates that readout variation is $\pm 2\%$. Thus, power calculated from the indicated flow might be 3% greater than assumed, so $K_q = 1.03$. If flow is higher than nominal, velocity will also be greater and credit can be taken for this. Thus, $K_v = 1.03$.

SAFETY

The hazard unique to this irradiation is that core swelling or fuel vibration will cause a cladding failure. Rapid corrosion of the metal might then follow with release of radioactive contaminants to the moderator.

The moderator and blanket gas will be monitored continuously for fission product release. Gross failure will be detected by either the delayed neutron monitor (DNM) or the scanning liquid photoneutron monitor (SLPM) that sequentially samples the coolant stream from each test assembly. The DNM has a delay time of about one minute; delay time for the SLPM is from one to three minutes. Small failures will be detected by either the low energy gamma monitor (LEGM) or the gaseous fission product monitor (GFPM), each of which have delay times of about 20 minutes. At least one of the fast response (DNM or SLPM) monitors and one of the more sensitive monitors (LEGM or GFPM) will always be functioning while the reactor is at power. If it is determined that the element has failed, the reactor will be shut down and the assembly discharged to a failed element container in the spent fuel basin.

INTERIM INSPECTIONS

The reactor will be shut down and the TMT-1 assemblies discharged for inspection at the RBOF at approximately the accumulated exposures requested in Appendix C-1.

CHARGE AND DISCHARGE

The fuel assembly will be charged and discharged as a unit. During discharge, the maximum fuel surface temperature will not be allowed to exceed 350°C. Table III gives times for the hottest irradiated element to heat adiabatically from 50 to 350°C. Cooling water will be applied to the fuel if these times are exceeded during transfer.

The values in Table III are calculated on a conservative basis because accurate values for decay power of thorium are not presently available. Table III will be revised when calculations of thorium decay power are completed.

TABLE Ia

ESTIMATED INITIAL OPERATING CHARACTERISTICS

Reactor pressure, psig	1200
Coolant inlet temperature, °C	185
Assembly coolant flow, gpm	150(a)
Assembly coolant temp rise, °C	30.5
Assembly coolant power, kw	1200
Axial max/avg power	1.8
Max nominal specific power, watts/gram Th	62(b)
Max nominal core temperature, °C	500

	<u>Outer Channel</u>	<u>Inner Channel</u>
Heat split, %	56.0	44.0
Max nominal heat flux, pcu/(hr)(ft ²)	400,000	455,000
Heat transfer area, ft ² /ft	0.667	0.484
Equivalent uniform core length, ft	8.16	8.16
Coolant flow, gpm	82.8	61.2
Coolant velocity, ft/sec	18.1	18.8
Coolant temp rise, °C	31.1	33.2
Coolant flow area, in. ²	1.47	1.04
Coolant channel De, in.	0.32	0.35
Nominal effluent temp, °C	216	218
Max (with HCF) effluent temp, °C	234	234
Sat. temp at effluent, °C	296	296
Min (with HCF) effluent temp, °C	62	62
Max nominal surface temp, °C	263	266
Max nominal interface temp, °C	393	406
Min BOSH (with HSF & HCF)	2.3	2.1

(a) Includes 6 gpm axial purge through inner housing.

(b) Includes moderator heating.

TABLE IbESTIMATED OPERATING CHARACTERISTICS WITH O-1 DRIVERS

Reactor pressure, psig	1400
Coolant inlet temperature, °C	226
Assembly coolant flow, gpm	150(a)
Assembly coolant temperature rise, °C	27.0
Assembly coolant power, kw	1080
Axial max/avg power	1.8
Max nominal specific power, watts/gram Th	56(b)
Max nominal core temperature, °C	515

	<u>Outer Channel</u>	<u>Inner Channel</u>
Heat split, %	56.0	44.0
Max nominal heat flux, pcu/(hr)(ft ²)	379,000	411,000
Heat transfer area, ft ² /ft	0.667	0.484
Equivalent uniform core length, ft	8.16	8.16
Coolant flow, gpm	82.8	61.2
Coolant velocity, ft/sec	18.1	18.8
Coolant temperature rise, °C	27.4	29.1
Coolant flow area, in. ²	1.47	1.04
Coolant channel De, in.	0.32	0.35
Nominal effluent temp, °C	253	255
Max (with HCF) effluent temperature, °C	269	269
Saturation temp at effluent, °C	307	307
Minimum subcooling, °C	38	38
Max nominal surface temperature, °C	300	304
Max nominal interface temperature, °C	415	429
Min BOSF (with HSF & HCF)	1.9	1.8

(a) Includes 6 gpm axial purge through inner housing.

(b) Includes moderator heating.

TABLE II
HOT SPOT AND HOT CHANNEL FACTORS

Effect	K_g		K_t		K_v	
	Outer	Inner	Outer	Inner	Outer	Inner
1. Circumferential neutron flux variation	1.05	1.05	1.10	1.10	-	-
2. Axial power shape	1.03	1.03	-	-	-	-
3. Core thickness variation	1.05	1.05	1.05	1.05	-	-
4. Fuel (U-235) segregation	1.10	1.10	-	-	-	-
5. Heat split uncertainty	1.02	1.02	1.02	1.02	-	-
6. Flow split uncertainty	-	-	1.02	1.02	0.98	0.98
7. Nonbonds	1.04	1.04	-	-	-	-
8. Rib contact	1.06	1.05	-	-	-	-
9. Eccentricity	-	-	1.26	1.20	0.84	0.87
10. Temperature monitoring	1.03	1.03	1.03	1.03	-	-
11. Flow monitoring	1.03	1.03	-	-	1.03	1.03
Over-all →	1.49	1.48	1.56	1.49	0.85	0.88

TABLE III
ALLOWABLE TIMES WITHOUT COOLING DURING DISCHARGE

Assumed max specific power: 62 watts/gram Th
(Coolant power of
1.2 MW at $n_K = 1.8$)

Time After Shutdown	Exposure →	Elapsed time for hottest part of element to heat adiabatically from 50 to 350°C, minutes		
		34.7 days	116 days	347 days
5 hours		1.4	1.1	1.0
10		1.6	1.4	1.2
24		2.1	1.7	1.5
2 days		2.7	2.1	1.9
5		4.0	2.9	2.5
10		5.8	3.8	3.1
20		9.1	5.6	4.3
40		18	8.7	6.1

TABLE I
SUMMARY OF COMPOSITION FOR PROTOTYPE MOLA

Melt Number	Type Charge	Uranium Depleted (g/g)	Gentile Analysis				Mold I.D. (inches)	Cone Diameter (inches)	Charge Weight (pounds)	Diameter Height (inches)	Casting Height (On Outside)	Casting Surface	Used with Billet Number	Remarks
			n/o Uranium	Carbon (ppm)	Top	Bottom								
TX-1370	Virgin Metal	2.50	1.43	1.42	1100	1250	7.0	2.3	175.9	----	----	Four-drip melt	---	-----
TX-1373	"	1.50	1.55	1.59	1250	1200	7.0	2.3	175.0	174.5	12-3/8	Horizontal, large and splash particles	---	Secondary shrink hole failed to clean up.
TX-1382	Remelt TX-1370, & 1373	1.50	1.48	1.56	1520	1530	7.5	Top-1.8 Bot-2.2	190.75	189.0	11-5/8	" "	---	-----
TX-1384	Virgin Metal	1.61(2)	1.58	1.50	3680	3060	7.5	Top-1.7 Bot-2.1	180.5	189.25	11-1/2	" "	---	Granules fell into mold
TX-1407	"	1.61	1.64	1.65	1560	1440	7.5	Top-1.7 Bot-2.1	201.5	196.5	32	" "	1-1	Larger than average skull
TX-1414	"	1.61	1.50	1.56	2050	1930	7.5	Top-1.7 Bot-2.1	200.75	194.25	11-7/8	" "	1-3	-----
TX-1419	"	1.61	1.55	1.60	1505	1430	7.5	Top-1.7 Bot-2.1	200.7	185	11-7/8	" "	1-2	Larger than average skull
TX-1454	"	1.505(3)	1.56 1.57	1.55	1100	1470	7.5	Top-1.7 Bot-2.1	199.6	198.0	11-3/4	" "	2-4	-----

(1) Depleted uranium used for all prototype melts.

(2) Change specified in desired composition.

(3) Second change dictated as a result of refinements in reactor
physics calculations.

TABLE II
EXTRUSION CONSTANTS FOR Th-U AND ZIRCALOY-2

Extrusion Number	Chemical Analysis of Th-U(1)		Billet Temp. (°C)	Extrusion Constant K		Ratio of Extrusion Constants, Relative to Zr-2 (Percent) $\frac{K_{Th-U} - K_{Zr-2}}{K_{Zr-2}} (100)$
	Uranium (w/o)	Carbon (ppm)		Zr-2 (ksi) (2)	Th-U (ksi)	
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 press: NMI 300-ton

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

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

TABLE III
HOT HARDNESS OF Th-U AND ZIRCALOY-2

Alloy ⁽¹⁾	DPH Number		
	620 °C	675 °C	730 °C
Th-1.55 w/o U with 1350 ppm Carbon	42	29	23
Th-1.45 w/o U with 1520 ppm Carbon	41	30	24
Nickel-free Zircaloy-2	28	17	12
Standard Zircaloy-2	23	16	12

(1) 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. H2C-1677.

TABLE IV
PROTOTYPE BILLET CORES

<u>Proto- type Billet Number</u>	<u>Casting Number</u>	<u>Uranium (w/o)</u>	<u>Carbon (ppm)</u>	<u>Pre- shape Design</u>	<u>Results of Final Inspection</u>	
					<u>Dimensional Deviations</u>	<u>Surface Defects</u>
1-1	TX-1407	1.64	1500	Fig. 4	None	None
1-2	TX-1419	1.58	1460	Fig. 6	Length - 7.580 inches (0.060 inch short)	None
1-3	TX-1414	1.53	1980	Fig. 4	None	None
1-4	TX-1454	1.56	1280	Fig. 4(1)	None	Graphite inclu- sion, 0.03" in diameter x 0.06" depth, on outside surface 2.0" from front end.

(1) Core machined to the shorter overall length of 7.549 inches used for enriched cores.

TABLE V

STOCK PREPARATION FOR ZIRCALOY-2 AND ZIRCONIUM COMPONENTS

		Harvey Aluminum Inc.			
Item	Composition	Identification No.	Condition as Received at NM	Processing after Receipt at NM	
Outer sleeves	Zircaloy-2	H2C-1808	Seamless tubing, 7.02 in. OD x 5.50 in. ID produced from forged bar by beta treating with a water quench followed by extrusion at a reduction of at least 7:1 ⁽¹⁾	Machined to final size	
Inner sleeves for all but billet 1-4 and 2-3	Zircaloy-2	H2C-1677-2-34	Forged bar, 8 in. dia.	} Drilled to 2-3/16-in. ID, heated to 1830°F and water quenched, then extruded twice at 1450°F through a total reduction of 13.5:1 to give tubing of 2.86 in. OD x 1.80 in. ID for machining to final size	
Inner sleeves for billet 1-4 and 2-3	Zircaloy-2	H2C-1691	Forged bar, 8 in. dia.		
End seals	Zircaloy-2	H2C-1808	Forged bar, beta treated with a water quench and machined to 6.8 in. OD x 2.5 in. ID ⁽¹⁾	Machined to final size	
Knee pieces	Zirconium	H2C-1605	Forged bar, 6.9 in. dia.	Heated to 1830°F and water quenched, upset to 7.05 in. dia. for machining to final size	
Dummy billets O-1 and D-2	Nickel-free Zircaloy-2	H2C-1639	Forged bar, beta treated with a water quench and machined to 7.1 in. dia. ⁽¹⁾	Machined to final size	
Dummy billet D-3	Nickel-free Zircaloy-2	H2C-1639	Forged bar, 8 in. dia.	Heated to 1830°F and water quenched before machining to final size	

⁽¹⁾ Assumed history based on specifications in telegram of 12/20/63 from E. E. Hayes of E. I. duPont de Nemours and Co. to G. A. Moudry of Harvey Aluminum Inc.

TABLE VI
CHEMICAL ANALYSES FOR ENRICHED CASTINGS

<u>Casting Number</u>	<u>Total U(1)</u>		<u>Carbon</u>	
	<u>Top</u> <u>(w/o)</u>	<u>Bottom</u> <u>(w/o)</u>	<u>Top</u> <u>(ppm)</u>	<u>Bottom</u> <u>(ppm)</u>
TX-1448(2)	1.59	1.58	1180	1010
TX-1451	1.53	1.53	2390	3030
TX-1453(3)	1.53	1.53	760	910

- (1) Ora.loy containing 93% ^{235}U used in melting;
multiply by 0.93 to obtain w/o ^{235}U .
- (2) A sample drilled from the midwall about $\frac{1}{2}$ inch
below the top of the hot top analyzed 1.59 w/o
total U and 1140 ppm C.
- (3) 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 w/o total
U and 1040 ppm C for the outside and 1.55 w/o
total U and 1010 ppm C for the inside.

TABLE VII
DESCRIPTION OF ENRICHED BILLET CORES

<u>Enriched Billet Number</u>	<u>Casting Number</u>	<u>Composition</u>		<u>Core Weight (grams)</u>	<u>Results of Final Inspection⁽¹⁾</u>
		<u>Total U (w/o)</u>	<u>Carbon (ppm)</u>		
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.

(1) Final measurements indicated all three cores were within the dimensions specified (i.e., as in Figure 4, except length specified for enriched cores was 7.549 ± 0.005 inch).

TABLE VIII

BILLET SHIPPING SCHEDULE TO SAVANNAH RIVER

<u>Date of Shipment</u>	<u>Number of Billets</u>	<u>Identification of Billets</u>
3/6/64	6	4 copper dummy billets and Zircaloy-2 billets Nos. 0-1 and 0-2
3/11/64	2	Prototype billets Nos. 1-1 and 1-2
3/13/64	2	Prototype billet No. 1-3 and Zircaloy-2 billet No. 0-3
5/14/64	4	Prototype billet No. 1-4; enriched billets Nos. 2-1, 2-2 and 2-3

TABLE IX

EXTRUSION DATA FOR PROTOTYPE Th-U TUBES

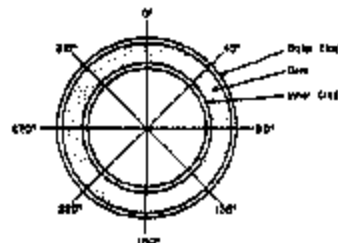
Tube No.	0.1	1.1	1.2	1.3
Material	Ni-free Zircaloy-2	Th-1.64 w/o U (natural)	Th-1.58 w/o U (natural)	Th-1.53 w/o U (natural)
Casting No.	-	TX-1407	TX-1419	TX-1414
Date extruded	4/1/64	4/2/64	4/2/64	4/2/64
Press capacity, tons	2750	2750	2750	2750
Ram speed, in./min	12	12	12	12
Tool diameter, inches				
Liner ID	7.200	7.200	7.200	7.200
Die ID ^(a)	2.573	2.573	2.573	2.573
Mandrel OD	1.831	1.831	1.831	1.831
Tool temperature, °C				
Liner & die	315 ±25	315 ±25	315 ±25	315 ±25
Mandrel & cut-off	370	370	370	370
Cut-off material	Copper	Copper	Copper	Copper
Lubricant	Aquadag prior to heating - Dildag just prior to extrusion			
Billet heating				
Furnace	Lindberg 40 Kw pot furnace			
Temp, (b) °C	775 ±15	775 ±15	775 ±15	775 ±15
Atmosphere	Reducing (graphite sleeve around billet)			
Total time	18 hrs	18 hrs	18 hrs-30 min	22 hrs-30 min
Reduction ratio	14:1	14:1	14:1	14:1
Extrusion force				
Max, tons	2100	2000	2000	2000
Extrusion constant K				
Zircaloy, ksi	21	20	20	20

(a) Integral die and core.

(b) Read at inside wall of billet before removal from furnace.

Detailed description of Figure 6: This schematic diagram illustrates the genomic structure of the Hm-1 gene. At the top, a horizontal axis marks positions from -1000 to +1800 bp. Below this, a series of boxes represent exons, connected by lines representing introns. Arrows on the intron lines indicate the direction of splicing. The size of each exon is labeled in base pairs (bp) above the box. The exons are numbered 1 through 9. Below the main diagram, two rows of labels identify specific regions: 'Exon 1' corresponds to positions -1000 to -700, and 'Exon 2' corresponds to positions -700 to -400.

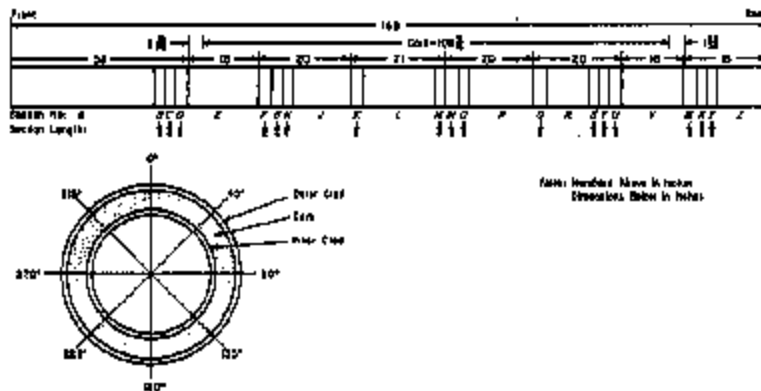
Region	Start (bp)	End (bp)	Size (bp)
Exon 1	-1000	-700	300
Intron 1	-700	-600	100
Exon 2	-600	-400	200
Intron 2	-400	-300	100
Exon 3	-300	-200	100
Intron 3	-200	-100	100
Exon 4	-100	0	100
Intron 4	0	100	100
Exon 5	100	200	100
Intron 5	200	300	100
Exon 6	300	400	100
Intron 6	400	500	100
Exon 7	500	600	100
Intron 7	600	700	100
Exon 8	700	800	100
Intron 8	800	900	100
Exon 9	900	1000	100



News: Monsters Move In, James
Dinwiddie, 3/10/97, p. 10

<u>Identify</u>	<u>Type</u>	<u>0°</u>	<u>4.5°</u>	<u>90°</u>	<u>135°</u>	<u>180°</u>	<u>225°</u>	<u>270°</u>	<u>315°</u>
D	OD	2.557	2.558	2.560	2.554	-	-	-	-
	ID	1.849	1.851	1.856	1.853	-	-	-	-
	Outer clad	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030
	End seal	0.285	0.285	0.285	0.285	0.285	0.280	0.275	0.280
	Inner clad	0.030	0.030	0.030	0.030	0.035	0.035	0.040	0.030
F	OD	2.550	2.551	2.551	2.550	-	-	-	-
	ID	1.848	1.842	1.843	1.843	-	-	-	-
	Outer clad	0.040	0.040	0.040	0.040	0.040	0.040	0.035	0.040
	Core	0.280	0.280	0.280	0.285	0.285	0.285	0.285	0.280
	Inner clad	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030
G	Outer clad	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040
	Core	0.280	0.280	0.280	0.280	0.280	0.285	0.280	0.280
	Inner clad	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030
H	Outer clad	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035
	Core	0.280	0.280	0.285	0.285	0.285	0.285	0.285	0.285
	Inner clad	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030
K	OD	2.548	2.549	2.548	2.548	-	-	-	-
	ID	1.842	1.842	1.841	1.841	-	-	-	-
	Outer clad	0.030	0.030	0.030	0.030	0.030	0.030	0.031	0.030
	Core	0.290	0.290	0.290	0.290	0.290	0.290	0.290	0.290
	Inner clad	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030
R	OD	2.550	2.549	2.549	2.549	-	-	-	-
	ID	1.841	1.840	1.841	1.841	-	-	-	-
	Outer clad	0.030	0.030	0.035	0.035	0.030	0.030	0.035	0.030
	Core	0.280	0.280	0.285	0.285	0.285	0.280	0.285	0.280
	Inner clad	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030
O	Outer clad	0.035	0.035	0.035	0.030	0.030	0.030	0.035	0.035
	Core	0.285	0.285	0.285	0.290	0.290	0.285	0.285	0.285
	Inner clad	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030
Q	OD	2.550	2.549	2.549	2.548	-	-	-	-
	ID	1.840	1.839	1.840	1.840	-	-	-	-
	Outer clad	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030
	Core	0.285	0.285	0.285	0.285	0.290	0.290	0.290	0.290
	Inner clad	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030
B	Outer clad	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030
	Core	0.285	0.285	0.285	0.285	0.285	0.290	0.290	0.290
	Inner clad	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035
T	Outer clad	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.035
	Core	0.285	0.285	0.285	0.285	0.285	0.285	0.290	0.285
	Inner clad	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035
U	OD	2.550	2.551	2.549	2.548	-	-	-	-
	ID	1.840	1.839	1.839	1.840	-	-	-	-
	Outer clad	0.035	0.030	0.030	0.030	0.030	0.035	0.035	0.0

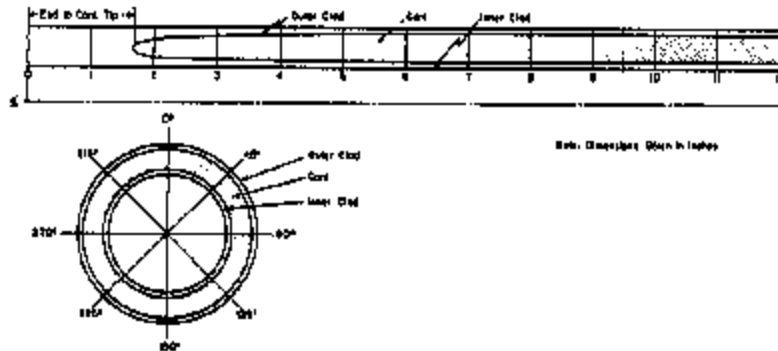
DIMENSIONAL CHARACTERISTICS FOR PROTOTYPE TH-U TUBES,
 TUBE NO. 1.2



Identity	Item	D ⁰	45°	90°	135°	180°	225°	270°	315°
D	OD	2.550	2.553	2.556	2.554	-	-	-	-
	ID	1.845	1.844	1.844	1.844	-	-	-	-
	Outer clad	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030
	End seal	0.285	0.285	0.285	0.285	0.285	0.285	0.285	0.285
	Inner clad	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030
F	OD	2.545	2.547	2.547	2.544	-	-	-	-
	ID	1.839	1.839	1.838	1.839	-	-	-	-
	Outer clad	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035
	Core	0.280	0.280	0.280	0.285	0.285	0.285	0.285	0.285
	Inner clad	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030
G	Outer clad	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035
	Core	0.280	0.280	0.280	0.280	0.280	0.285	0.285	0.280
	Inner clad	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030
H	Outer clad	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035
	Core	0.280	0.280	0.285	0.285	0.280	0.280	0.285	0.285
	Inner clad	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030
K	OD	2.545	2.546	2.546	2.545	-	-	-	-
	ID	1.839	1.839	1.840	1.839	-	-	-	-
	Outer clad	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035
	Core	0.285	0.285	0.285	0.285	0.285	0.285	0.285	0.285
	Inner clad	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030
L	OD	2.545	2.544	2.546	2.545	-	-	-	-
	ID	1.838	1.838	1.838	1.838	-	-	-	-
	Outer clad	0.030	0.035	0.035	0.035	0.035	0.035	0.030	0.030
	Core	0.280	0.285	0.285	0.285	0.285	0.285	0.285	0.285
	Inner clad	0.035	0.030	0.030	0.035	0.030	0.030	0.035	0.035
O	Outer clad	0.030	0.030	0.035	0.035	0.035	0.035	0.035	0.035
	Core	0.280	0.280	0.280	0.280	0.300	0.295	0.295	0.285
	Inner clad	0.035	0.030	0.030	0.030	0.030	0.030	0.030	0.030
Q	OD	2.547	2.544	2.544	2.545	-	-	-	-
	ID	1.839	1.841	1.839	1.839	-	-	-	-
	Outer clad	0.035	0.035	0.030	0.035	0.035	0.035	0.030	0.035
	Core	0.280	0.285	0.280	0.280	0.280	0.285	0.285	0.285
	Inner clad	0.030	0.030	0.030	0.030	0.030	0.030	0.035	0.030
R	Outer clad	0.030	0.030	0.030	0.035	0.035	0.035	0.035	0.030
	Core	0.285	0.280	0.285	0.280	0.280	0.280	0.285	0.285
	Inner clad	0.035	0.035	0.030	0.030	0.030	0.030	0.030	0.035
T	Outer clad	0.035	0.035	0.030	0.035	0.030	0.030	0.035	0.035
	Core	0.285	0.285	0.285	0.285	0.285	0.285	0.285	0.285
	Inner clad	0.035	0.035	0.030	0.030	0.035	0.035	0.035	0.035
U	OD	2.546	2.547	2.546	2.544	-	-	-	-
	ID	1.840	1.839	1.839	1.839	-	-	-	-
	Outer clad	0.035	0.035	0.030	0.030	0.030	0.035	0.035	0.035
	Core	0.280	0.280	0.280	0.280	0.280	0.280	0.280	0.280
	Inner clad	0.030	0.030	0.035	0.030	0.030	0.030	0.030	0.030
V	OD	2.554	2.557	2.554	2.549	-	-	-	-
	ID	1.847	1.850	1.848	1.849	-	-	-	-
	Outer clad	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030
	End seal	0.290	0.290	0.290	0.295	0.290	0.285	0.290	0.280
	Inner clad	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030

TABLE XXV

END SHAPE - PROTOTYPE T8-V TURNS, TURN NO. 1-1



A - FRONT END

Location	End to Core Tip	Item	1	2	3	4	5	6	7	8	9	10	11	12
0°	1-27/32 (1)	Outer clad	0.205	0.105	0.072	0.068	0.060	0.053	0.047	0.046	0.043	0.042	0.040	0.040
		Core	0.074	0.138	0.065	0.056	0.048	0.057*	0.058*	0.071	0.073	0.077	0.080	0.080
		Inner clad	0.069	0.092	0.050	0.045	0.040	0.040	0.040	0.036	0.035	0.032	0.030	0.030
45°	2-4/32	Outer clad	-	0.068	0.056	0.048	0.042	0.041	0.038	0.037	0.035	0.035	0.032	0.032
		Core	-	0.158	0.089	0.037	0.049*	0.057*	0.069*	0.068	0.069	0.075	0.080	0.080
		Inner clad	-	0.097	0.071	0.068	0.062	0.055	0.047	0.048	0.045	0.045	0.040	0.040
90°	2-5/32	Outer clad	-	0.097	0.073	0.070	0.062	0.055	0.050	0.048	0.045	0.043	0.041	0.041
		Core	-	0.158	0.084	0.039	0.047	0.055	0.050*	0.058*	0.071	0.078	0.080	0.080
		Inner clad	-	0.061	0.052	0.049	0.042	0.040	0.039	0.035	0.035	0.032	0.031	0.031
135°	1-30/32	Outer clad	0.070	0.058	0.053	0.043	0.043	0.043	0.040	0.038	0.037	0.037	0.036	0.036
		Core	0.095	0.122	0.085	0.039	0.043	0.055*	0.065*	0.070	0.073	0.080	0.085	0.085
		Inner clad	0.158	0.107	0.073	0.068	0.064	0.057	0.047	0.045	0.043	0.040	0.037	0.037
180°	1-27/32	Outer clad	0.158	0.110	0.079	0.075	0.065	0.059	0.053	0.049	0.046	0.045	0.042	0.042
		Core	0.103	0.182	0.081	0.033	0.042	0.055*	0.064*	0.068	0.073	0.080	0.085	0.085
		Inner clad	0.065	0.055	0.048	0.042	0.041	0.036	0.035	0.035	0.033	0.032	0.030	0.030
225°	2-3/32	Outer clad	-	0.052	0.053	0.050	0.045	0.041	0.040	0.038	0.037	0.035	0.034	0.034
		Core	-	0.209	0.080	0.034	0.032	0.058*	0.065*	0.072	0.077	0.081	0.085	0.085
		Inner clad	-	0.095	0.072	0.067	0.058	0.054	0.048	0.045	0.043	0.040	0.032	0.032
270°	2-7/32 (1)	Outer clad	-	0.089	0.076	0.071	0.062	0.054	0.049	0.046	0.044	0.044	0.044	0.040
		Core	-	0.090	0.085	0.036	0.030	0.059*	0.069*	0.073	0.075	0.077	0.082	0.082
		Inner clad	-	0.063	0.058	0.044	0.041	0.040	0.038	0.034	0.035	0.035	0.033	0.033
315°	2-6/32	Outer clad	-	0.080	0.067	0.057	0.055	0.048	0.045	0.042	0.042	0.040	0.037	0.037
		Core	-	0.094	0.080	0.043	0.032*	0.062*	0.068*	0.074	0.077	0.080	0.083	0.083
		Inner clad	-	0.068	0.056	0.049	0.047	0.043	0.038	0.035	0.037	0.037	0.034	0.034

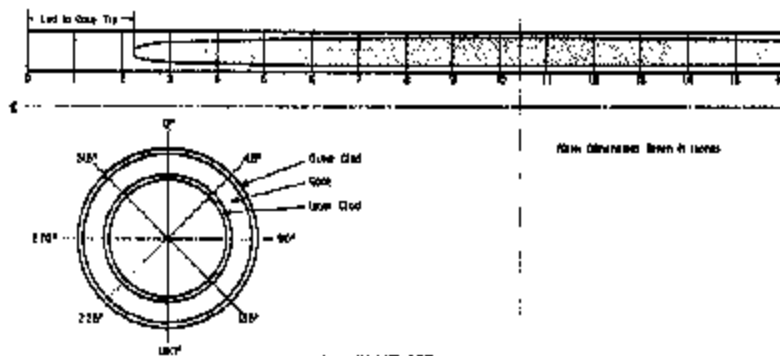
B - REAR END

45° (2)	2-8/32	Outer clad	-	0.095	0.068	0.051	0.042	0.038	0.037	0.035	0.034	0.033	0.030	0.030
		Core	-	0.132	0.082	0.050*	0.066*	0.076	0.080	0.084	0.084	0.084	0.087	0.087
		Inner clad	-	0.123	0.062	0.043	0.043	0.040	0.038	0.033	0.032	0.035	0.033	0.033
90°	2-1/32 (3)	Outer clad	-	0.104	0.075	0.057	0.045	0.040	0.038	0.038	0.035	0.035	0.032	0.032
		Core	-	0.129	0.228	0.047*	0.065*	0.073	0.080	0.080	0.083	0.085	0.085	0.085
		Inner clad	-	0.122	0.060	0.050	0.046	0.038	0.034	0.033	0.035	0.035	0.036	0.036
135°	2-4/32	Outer clad	-	0.095	0.068	0.051	0.040	0.038	0.036	0.035	0.034	0.035	0.032	0.032
		Core	-	0.139	0.085	0.053*	0.064*	0.072	0.080	0.082	0.081	0.085	0.085	0.085
		Inner clad	-	0.117	0.056	0.048	0.044	0.039	0.034	0.032	0.035	0.036	0.036	0.036
180°	2-8/32	Outer clad	-	0.103	0.074	0.057	0.042	0.042	0.038	0.038	0.039	0.033	0.032	0.032
		Core	-	0.180	0.014	0.047*	0.061*	0.067	0.078	0.076	0.077	0.080	0.080	0.080
		Inner clad	-	0.125	0.062	0.045	0.042	0.040	0.032	0.032	0.033	0.035	0.035	0.035
225°	2-17/32	Outer clad	-	0.104	0.072	0.055	0.041	0.040	0.039	0.037	0.035	0.034	0.032	0.032
		Core	-	0.101	0.010	0.032*	0.065*	0.073	0.081	0.082	0.084	0.085	0.087	0.087
		Inner clad	-	0.143	0.089	0.047	0.047	0.040	0.038	0.030	0.033	0.034	0.035	0.035
270°	2-4/32	Outer clad	-	0.109	0.079	0.058	0.045	0.042	0.040	0.040	0.037	0.035	0.033	0.033
		Core	-	0.075	0.182	0.046	0.058*	0.068*	0.073	0.073	0.080	0.085	0.085	0.085
		Inner clad	-	0.163	0.089	0.049	0.045	0.040	0.034	0.034	0.034	0.035	0.035	0.035
315°	2-20/32 (3)	Outer clad	-	0.122	0.085	0.063	0.046	0.040	0.040	0.039	0.036	0.036	0.035	0.035
		Core	-	0.074	0.195	0.050*	0.066*	0.079	0.085	0.086	0.086	0.089	0.090	0.090
		Inner clad	-	0.155	0.075	0.046	0.045	0.039	0.033	0.031	0.035	0.036	0.034	0.034

- (1) Shift as defined by minimum to maximum end to core tip dimension is 2-7/32 minus 1-27/32, or 2/16".
 Layer is defined as the distance from core tip to the point where the core is 90% of the nominal thickness, 0.090", or 0.061". The 90% core thickness point is shown falling between the dimensions (*) noted above.
 Average Layer is 2-24/32".
- (2) Data for 0° not taken.
- (3) Shift is 2-20/32 minus 2-1/32, or 19/32". Layer is shown to end between the dimensions (*) noted above.
 Average Layer is 2-11/16".

TABLE XIII

END SHAPE - PROTOTYPE No. V TURBINE, TUBE NO. 1.2



A - PROTOTYPE

Location	End to Case Tip	Line	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0°	2-27/32	Outer clad	-	0.140	0.205	0.095	0.092	0.082	0.073	0.068	0.050	0.045	0.048	0.042	0.038	0.038
		Core	-	0.044	0.163	0.178	0.183	0.200	0.213	0.225	0.244	0.258	0.242	0.254	0.275	0.277
		Inner clad	-	0.166	0.090	0.085	0.077	0.070	0.067	0.068	0.058	0.046	0.050	0.042	0.035	0.034
45°	2-30/32 (1)	Outer clad	-	0.135	0.109	0.100	0.092	0.087	0.075	0.068	0.055	0.049	0.043	0.042	0.040	0.039
		Core	-	0.093	0.151	0.170	0.180	0.190	0.205	0.224	0.238	0.247	0.255	0.264	0.270	0.274
		Inner clad	-	0.159	0.087	0.080	0.074	0.073	0.066	0.058	0.055	0.050	0.046	0.042	0.038	0.034
90°	2-21/32	Outer clad	-	0.113	0.096	0.088	0.081	0.072	0.065	0.058	0.050	0.045	0.042	0.038	0.038	0.038
		Core	-	0.090	0.165	0.175	0.182	0.200	0.223	0.237	0.248	0.258	0.263	0.270	0.273	0.275
		Inner clad	-	0.150	0.089	0.085	0.078	0.071	0.065	0.050	0.054	0.048	0.048	0.042	0.038	0.034
135°	2-15/32	Outer clad	-	0.110	0.100	0.098	0.081	0.073	0.066	0.057	0.050	0.044	0.042	0.040	0.038	0.035
		Core	-	0.145	0.167	0.180	0.195	0.211	0.225	0.240	0.251	0.260	0.268	0.278	0.275	0.284
		Inner clad	-	0.094	0.084	0.077	0.072	0.068	0.060	0.053	0.050	0.046	0.042	0.037	0.036	0.031
180°	2-10/32 (1)	Outer clad	-	0.108	0.092	0.081	0.079	0.072	0.066	0.055	0.048	0.043	0.042	0.039	0.036	0.030
		Core	-	0.130	0.171	0.180	0.198	0.213	0.228	0.238	0.249	0.258	0.267	0.274	0.287	0.284
		Inner clad	-	0.132	0.088	0.083	0.078	0.069	0.064	0.057	0.053	0.049	0.047	0.040	0.036	0.032
225°	2-6/32	Outer clad	-	0.116	0.100	0.093	0.082	0.072	0.065	0.055	0.049	0.043	0.042	0.040	0.037	0.036
		Core	-	0.100	0.168	0.174	0.193	0.207	0.223	0.233	0.250	0.262	0.266	0.272	0.279	0.285
		Inner clad	-	0.130	0.085	0.079	0.074	0.066	0.062	0.057	0.051	0.047	0.043	0.040	0.035	0.029
270°	2-4/32	Outer clad	-	0.113	0.094	0.087	0.081	0.074	0.065	0.058	0.050	0.045	0.042	0.042	0.038	0.033
		Core	-	0.073	0.163	0.178	0.192	0.205	0.228	0.236	0.251	0.258	0.263	0.270	0.274	0.285
		Inner clad	-	0.168	0.092	0.087	0.076	0.069	0.065	0.059	0.052	0.050	0.045	0.040	0.037	0.033
315°	2-28/32	Outer clad	-	0.128	0.108	0.101	0.092	0.084	0.075	0.062	0.056	0.040	0.045	0.042	0.039	0.036
		Core	-	0.075	0.154	0.163	0.185	0.198	0.213	0.230	0.243	0.255	0.262	0.270	0.276	0.288
		Inner clad	-	0.144	0.083	0.078	0.070	0.068	0.061	0.056	0.049	0.048	0.045	0.040	0.035	0.028

B - REAR END

0°	2-3/32	Outer clad	-	0.095	0.082	0.072	0.060	0.053	0.043	0.034	0.031	0.031	0.030	0.030	0.030	0.028
		Core	-	0.097	0.133	0.135	0.150	0.157	0.155	0.147	0.155	0.163	0.164	0.165	0.170	0.178
		Inner clad	-	0.147	0.105	0.084	0.068	0.058	0.056	0.055	0.054	0.049	0.048	0.045	0.042	0.038
45°	1-28/32 (2)	Outer clad	-	0.089	0.078	0.065	0.065	0.055	0.047	0.036	0.030	0.030	0.031	0.032	0.030	0.029
		Core	-	0.112	0.137	0.177	0.220	0.242	0.247	0.257	0.255	0.257	0.271	0.270	0.278	0.280
		Inner clad	-	0.147	0.116	0.085	0.075	0.067	0.059	0.050	0.057	0.055	0.052	0.048	0.045	0.040
90°	3-14/32	Outer clad	-	-	0.105	0.095	0.087	0.075	0.068	0.061	0.052	0.044	0.038	0.032	0.031	0.029
		Core	-	-	0.115	0.155	0.193	0.225	0.225	0.232	0.238	0.254	0.262	0.271	0.275	0.282
		Inner clad	-	-	0.130	0.101	0.074	0.061	0.050	0.056	0.059	0.053	0.050	0.047	0.040	0.039
135°	3-26/32 (2)	Outer clad	-	-	0.107	0.092	0.081	0.074	0.066	0.058	0.055	0.048	0.043	0.037	0.032	0.031
		Core	-	-	0.113	0.163	0.198	0.223	0.234	0.238	0.246	0.257	0.262	0.275	0.279	0.285
		Inner clad	-	-	0.185	0.109	0.079	0.063	0.062	0.060	0.058	0.055	0.054	0.047	0.045	0.041
180°	3-16/32	Outer clad	-	-	0.100	0.100	0.089	0.080	0.070	0.060	0.050	0.045	0.037	0.034	0.033	0.030
		Core	-	-	0.134	0.175	0.214	0.225	0.233	0.240	0.250	0.260	0.272	0.277	0.283	0.290
		Inner clad	-	-	0.118	0.085	0.060	0.056	0.058	0.055	0.054	0.049	0.045	0.042	0.041	0.038
225°	3-15/32	Outer clad	-	-	0.121	0.089	0.088	0.076	0.065	0.057	0.050	0.045	0.040	0.034	0.033	0.033
		Core	-	-	0.127	0.172	0.208	0.218	0.231	0.235	0.249	0.253	0.265	0.275	0.279	0.286
		Inner clad	-	-	0.125	0.090	0.066	0.058	0.050	0.050	0.053	0.054	0.049	0.045	0.040	0.037
270°	3-16/32	Outer clad	-	-	0.101	0.095	0.087	0.075	0.060	0.052	0.053	0.046	0.038	0.032	0.031	0.029
		Core	-	-	0.119	0.156	0.190	0.203	0.223	0.230	0.244	0.253	0.265	0.272	0.275	0.285
		Inner clad	-	-	0.127	0.097	0.072	0.060	0.055	0.055	0.053	0.050	0.047	0.045	0.044	0.038
315°	2-21/32	Outer clad	-	0.102	0.089	0.078	0.071	0.065	0.058	0.052	0.046	0.040	0.034	0.030	0.034	0.028
		Core	-	0.057	0.135	0.165	0.203	0.216	0.228	0.233	0.244	0.255	0.261	0.266	0.275	0.275
		Inner clad	-	0.125	0.118	0.095	0.069	0.060	0.053	0.057	0.054	0.053	0.052	0.047	0.046	0.036

(1) Shift is 2-30/32 minus 2-10/32, or 2-20/32. Taper is shown to end between the dimensions (*) noted above. Average Taper is 8-7/16".

(2) Shift is 3-26/32 minus 1-28/32, or 2-15/16". Taper is shown to end between the dimensions (*) noted above. Average Taper is 7-1/2".

TABLE XIV

EXTRUSION DATA FOR GROUP OF ENRICHED Th-U TUBES

Tube No.	1.4	2.1	2.2	2.3
Material	Th-1.56 w/o U (natural)	Th-1.58 w/o U (93% ²³⁵ U)	Th-1.53 w/o U (93% ²³⁵ U)	Th-1.53 w/o 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 (see Figure 11)

(b) Read at inside wall of billet before removal from furnace.

TABLE XV

SUMMARY OF DIMENSIONAL CHARACTERISTICS OF PROTOTYPE AND ENRICHED TUBES

Tube No.	0.1 (1)	1.1 (2)	1.2 (2)	1.3 (1)	1.4 (3)	2.1 (4)	2.2 (5)	2.3 (2)
	Material	Natural-U			Enriched-U			
Taper, in. Front								
Rear	NA	5-8 1/2/38	8-7/16	(6)	(6)			(6)
Shift, in. Front								
Rear	NA	5/16	5/8	(6)	(6)			(6)
Width + taper, in. Front								
Rear	NA	6-3/32	9-1/16	(6)	(6)			(6)
OD, w/o Cu, in. avg (5)		2.571	2.572	2.569	2.566	-	-	-
ID, w/o Cu, in. avg (6)		1.835	1.836	1.831	1.829	-	-	-
OD, w/o Cu, in. avg (7)		2.547	2.548	2.545	2.542	2.540		2.539
ID, w/o Cu, in. avg (7)		1.844	1.841	1.840	1.837	1.830		1.828
Box, before straightening, in. max		3/16	15/16	9/16	9/16	-	-	-
Box, 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	0.359	0.356		0.358
Outer cladding, in. avg		NA	0.038	0.034	-	-		-
min		NA	0.030	0.030	-	-		-
max		NA	0.045	0.036	-	-		-
Core, in. avg		NA	0.266	0.265	-	-		-
min		NA	0.260	0.260	-	-		-
max		NA	0.280	0.300	-	-		-
Inner cladding, in. avg		NA	0.031	0.031	-	-		-
min		NA	0.030	0.030	-	-		-
max		NA	0.035	0.035	-	-		-

(1) Tubes 0.1, and 1.3 were used for flow testing.

(2) Tubes 1.1, and 1.2 were destructively examined.

(3) 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.

(4) Tubes 2.1 and 2.3 were designated as irradiation candidates and were irradiated in the BWR.

(5) 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.

(6) These dimensions are based on a 4-1/8-in. all copper sheath on the ID and a 12-mil copper sheath on the OD.

(7) These dimensions are averaged over the uniform core and were taken prior to final etching of tubes.

(8) Approximately 1-1/8 mils is removed from each surface during etching.

(9) 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.

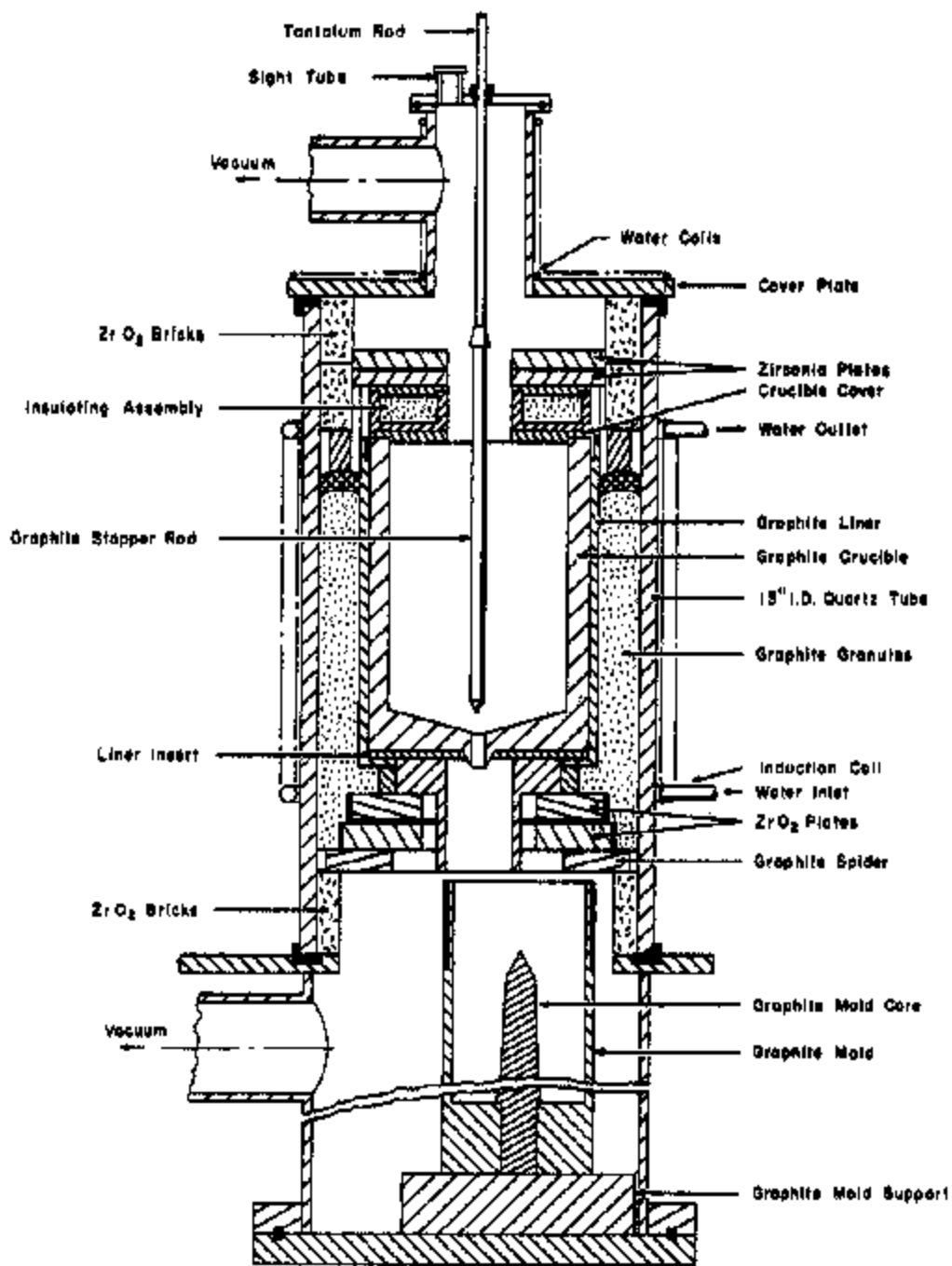


FIGURE 1
BOTTOM-POUR VACUUM INDUCTION MELTING FURNACE

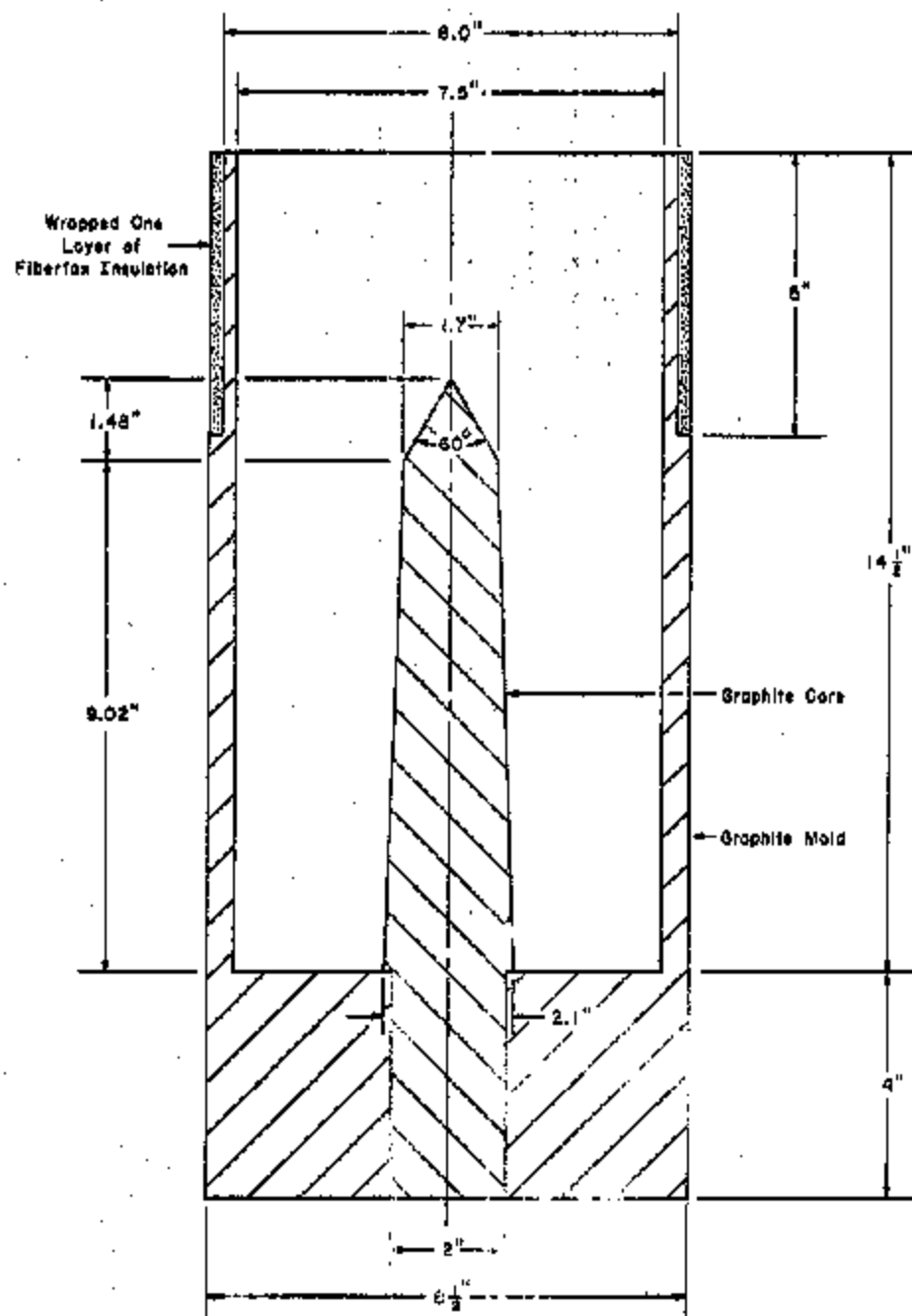
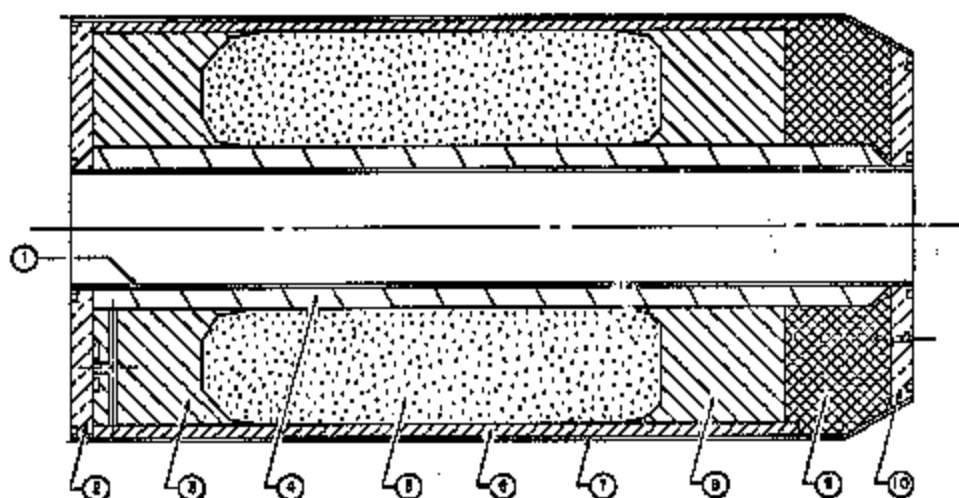


FIGURE 2

MOLD AND CORE FOR THORIUM-URANIUM ALLOY CASTINGS



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

FIGURE 3

COMPOSITE BILLET ASSEMBLY FOR THORIUM-URANIUM TUBULAR ELEMENTS



ZIRCALOY-2 END SEAL DESIGN USED FOR PROTOTYPE BILLET 1-1, 1-3 AND 1-4

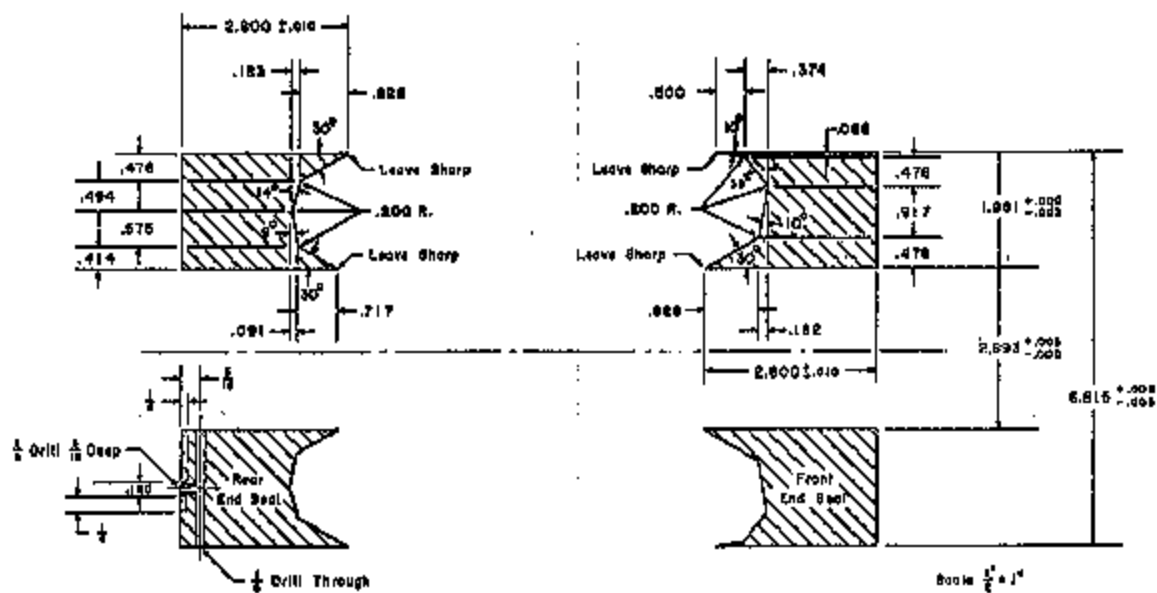


FIGURE 7
ZIRCALOY-2 END SEAL DESIGN USED FOR PROTOTYPE BILLET 1-2

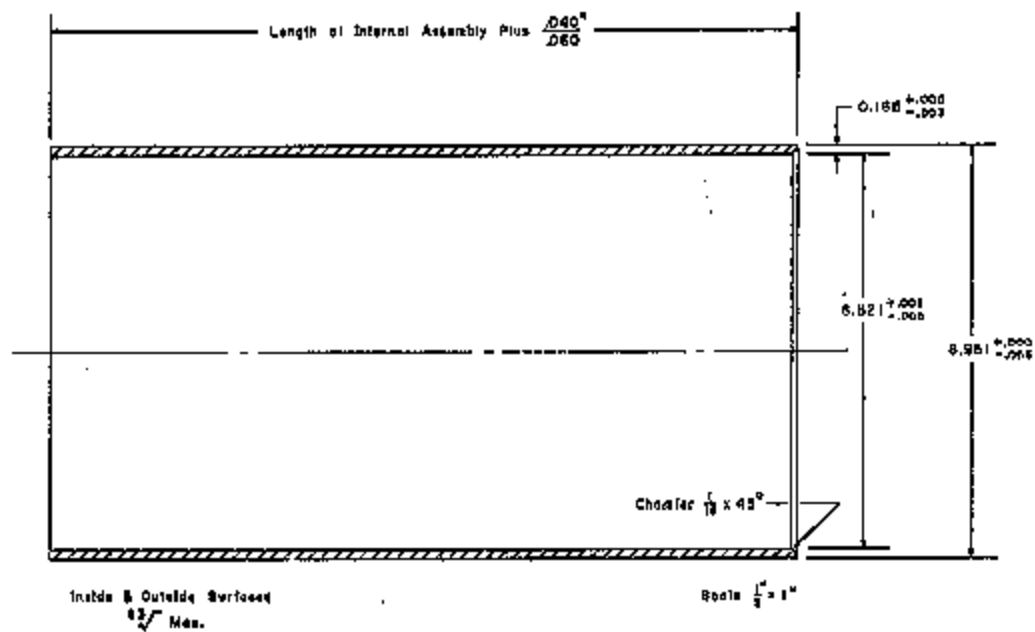


FIGURE 8
ZIRCALOY-2 OUTER SLEEVE DESIGN

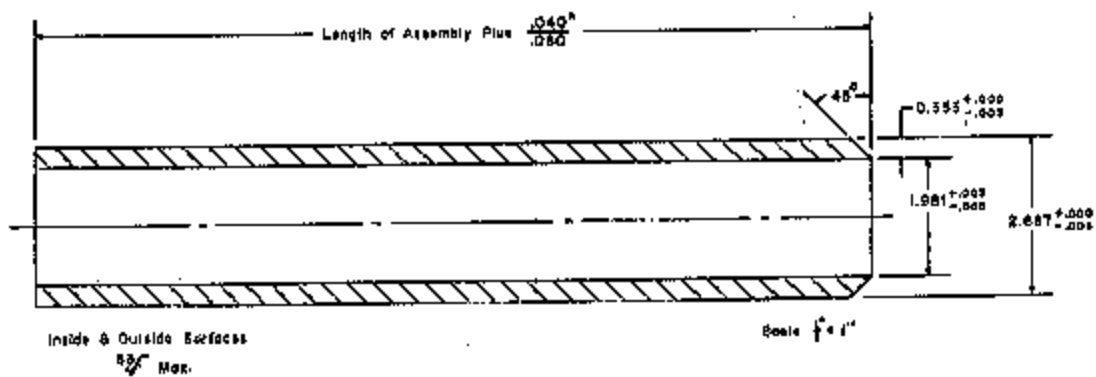


FIGURE 9
ZIRCALOY-2 INNER SLEEVE DESIGN

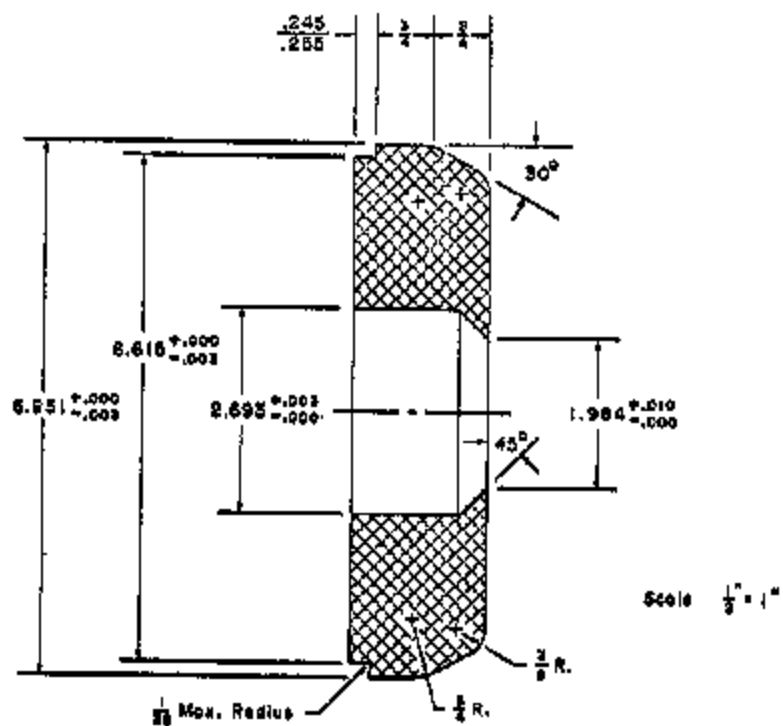


FIGURE 10
ZIRCONIUM NOSE PIECE DESIGN

FIGURE 12

EARLY ROTAX IEM DATA SHEET FOR Th-235 U ASSEMBLY NO. TWT 1-2

Date:	8/31/64	Channel Effluent:	214.6 °C
Delta T:	28.9 °C	Surface Temperature:	252.5 °C
Flow:	125 gpm	Core Temperature:	506.6 °C
Inlet:	183.4 °C	Heat Flux:	467.377 pcu/hr-ft ²
Power:	1.187 MW		

Layer	Power Shape ⁽¹⁾	Spec. Expos ⁽²⁾	Core Temp ⁽³⁾	Channel Temperature ⁽⁴⁾		Surface Temperature ⁽⁵⁾		Surface Heat Flux ⁽⁶⁾		Volumetric Heat Generation ⁽⁷⁾	Spec. Power ⁽⁸⁾
				Inner	Outer	Inner	Outer	Inner	Outer		
1	0.023	3.5	187.3	183.4	183.4	184.1	184.1	0.572E 04	0.528E 04	0.455E 06	0.7
2	0.090	13.7	193.9	183.5	183.5	186.4	186.3	0.226E 05	0.208E 05	0.180E 07	2.7
3	0.157	25.5	212.2	183.7	183.7	189.2	188.9	0.419E 05	0.387E 05	0.334E 07	5.0
4	0.259	39.6	228.1	184.0	184.0	192.5	192.1	0.651E 05	0.601E 05	0.518E 07	7.8
5	0.369	56.6	247.4	184.5	184.4	196.6	196.0	0.930E 05	0.858E 05	0.740E 07	11.1
6	0.502	76.8	270.3	185.2	185.1	201.6	200.7	0.126E 06	0.117E 06	0.101E 08	15.0
7	0.558	100.7	297.3	185.1	185.9	207.7	206.5	0.156E 06	0.153E 06	0.132E 08	19.7
8	0.841	128.7	328.9	187.2	187.0	214.9	213.3	0.212E 06	0.195E 06	0.169E 08	25.2
9	1.059	162.2	366.3	188.7	188.4	223.5	221.5	0.267E 06	0.246E 06	0.212E 08	31.8
10	1.333	204.1	412.8	190.6	190.1	234.4	231.8	0.336E 06	0.310E 06	0.267E 08	40.0
11	1.606	245.8	459.0	192.9	192.3	245.6	242.5	0.404E 06	0.373E 06	0.322E 08	48.1
12	1.777	272.0	488.8	195.5	194.8	253.9	250.3	0.447E 06	0.413E 06	0.356E 08	53.3
13	1.856	284.2	504.2	198.3	197.5	259.3	255.5	0.467E 06	0.431E 06	0.372E 08	55.6
14	1.855	283.9	506.6	201.2	200.2	262.2	258.2	0.467E 06	0.431E 06	0.372E 08	55.6
15	1.777	272.1	496.9	204.1	202.9	262.5	258.4	0.447E 06	0.413E 06	0.356E 08	53.3
16	1.630	249.5	475.8	206.7	205.4	260.3	256.3	0.410E 06	0.379E 06	0.327E 08	48.9
17	1.481	217.5	444.3	209.1	207.6	255.8	252.0	0.358E 06	0.330E 06	0.285E 08	42.6
18	1.153	179.1	404.4	211.1	209.5	249.3	245.8	0.293E 06	0.270E 06	0.233E 08	34.9
19	0.877	134.3	359.0	212.7	211.0	241.5	238.4	0.221E 06	0.204E 06	0.175E 08	26.3
20	0.586	89.8	311.9	213.9	212.1	233.1	230.4	0.148E 06	0.136E 06	0.118E 08	17.6
21	0.327	50.1	269.1	214.6	212.7	225.3	222.9	0.824E 05	0.760E 05	0.656E 07	9.8

(1) Dimensionless number representing axial power distribution.

(2) Watt-days/gram.

(3) All temperatures in °C.

(4) pcu/hr-ft². Example: 0.572E 04 = 0.572 X 10⁴.(5) pcu/hr-ft³. Example: 0.455E 06 = 0.455 X 10⁶.

(6) Watts/gram of core material (Th-235).

FIGURE 13

LAST ROTAX IBM DATA SHEET FOR Th-²³⁵U ASSEMBLY NO. TWT 1-2

Date: 12/1/64 Channel Effluent: 213.3 °C
 Delta T: 29.4 °C Surface Temp.: 232.3 °C
 Flow: 156 gpm Core Temperature: 464.3 °C
 Inlet: 181.6 °C Heat Flux: 406,508 pou/hr-ft²
 Power: 1,215 MW

Layer	Power Shape(1)	Spec. p Expos.	Core Temp. (3)	Channel Temperature (3)		Surface Temperature (3)		Surface Heat Flux (4)		Volumetric Heat Generation (5)	Spec. Power (6)
				(Inner)	(Outer)	(Inner)	(Outer)	(Inner)	(Outer)		
1	0.043	82.7	189.6	181.6	181.6	183.1	183.0	0.117E 05	0.106E 05	0.930E 06	1.4
2	0.176	324.0	212.6	181.8	181.8	187.7	187.4	0.455E 05	0.419E 05	0.362E 07	5.4
3	0.319	594.0	237.9	182.2	182.1	192.9	192.3	0.823E 05	0.760E 05	0.655E 07	9.8
4	0.479	904.7	266.0	182.6	182.7	196.6	196.0	0.123E 06	0.114E 06	0.982E 07	14.7
5	0.654	1239.3	296.9	183.7	183.6	205.6	204.4	0.169E 06	0.156E 06	0.134E 08	20.1
6	0.841	1653.6	329.7	184.9	184.7	213.0	211.4	0.217E 06	0.200E 06	0.173E 08	25.8
7	1.029	2078.7	362.9	186.4	186.1	220.8	218.8	0.265E 06	0.245E 06	0.211E 08	31.6
8	1.208	2512.6	394.6	188.1	187.7	228.5	226.2	0.311E 06	0.287E 06	0.248E 08	37.1
9	1.366	2921.6	422.7	190.2	189.7	233.9	233.1	0.352E 06	0.325E 06	0.280E 08	41.9
10	1.498	3262.4	446.8	192.4	191.8	242.6	239.5	0.386E 06	0.356E 06	0.307E 08	46.0
11	1.565	3485.1	460.0	194.9	194.1	247.2	243.9	0.403E 06	0.372E 06	0.321E 08	48.0
12	1.577	3573.3	464.3	197.4	196.4	250.1	246.6	0.407E 06	0.375E 06	0.324E 08	48.4
13	1.551	3550.4	462.4	199.8	198.8	251.7	248.2	0.400E 06	0.369E 06	0.318E 08	47.6
14	1.466	3446.2	455.4	202.2	201.0	252.3	248.7	0.366E 06	0.336E 06	0.307E 08	45.9
15	1.411	3243.8	443.7	204.6	203.2	251.8	248.1	0.364E 06	0.336E 06	0.290E 08	43.3
16	1.296	2954.5	426.5	206.7	205.2	250.1	246.5	0.334E 06	0.308E 06	0.266E 08	39.8
17	1.146	2580.8	403.5	208.7	207.0	247.0	243.5	0.295E 06	0.273E 06	0.235E 08	35.2
18	0.961	2131.1	374.0	210.3	208.6	242.5	239.2	0.248E 06	0.229E 06	0.197E 08	29.5
19	0.745	1627.3	339.0	211.7	209.9	236.6	233.6	0.192E 06	0.177E 06	0.153E 08	22.9
20	0.512	1103.4	300.3	212.7	210.8	229.8	227.1	0.132E 06	0.122E 06	0.105E 08	15.7
21	0.293	623.6	263.2	213.3	211.4	223.1	220.7	0.745E 05	0.696E 05	0.601E 07	9.0

(1) Dimensionless number representing axial power distribution

(2) Watt-days/gram.

(3) All temperatures in °C.

(4) pou/hr-ft². Example: 0.117E 05 = 0.117 X 10⁵.(5) pou/hr-ft³. Example: 0.930E 06 = 0.930 X 10⁶.(6) Watts/gram of core material (Th-²³⁵U).

FIGURE 14
TIME-WEIGHTED AVERAGE VALUES FOR Th-²³⁵ ASSEMBLY NO. TWT 1-2

Layer	Core Temp. (°C)	Surface Temperature (°C)		Surface Heat Flux ⁽¹⁾		Specific Power ⁽²⁾
		(Inner)	(Outer)	(Inner)	(Outer)	
1	188.4	183.2	182.1	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	0.604E 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	28.5
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	467.6	250.4	247.0	0.412E 06	0.380E 06	49.1
13	468.6	252.7	249.1	0.410E 06	0.378E 06	48.8
14	462.4	253.5	249.6	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

(1) pou/hr-ft^2 . Example: 0.953E 04 = 0.953×10^4 .

(2) Watts/gram of core material (Th-²³⁵U).

FIGURE 15
VARIABLES VERSUS SPECIFIC EXPOSURE FOR HOTTEST REGION OF
Th-235U ASSEMBLY NO. TWT 1-2

Layer 13 (76 inches from top of tube)

Spec. Expos. (1)	Core Temp. (2)	Channel Temperature (2)		Surface Temperature (2)		Surface Heat Flux (3)		Volumetric Heat Generation (4)	Specific Power (5)
		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	54.2
759.4	494.0	198.8	197.8	257.6	253.8	0.451E 06	0.416E 06	0.355E 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	0.367E 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	487.4	199.5	198.5	250.5	247.0	0.393E 06	0.362E 06	0.313E 08	46.7
3560.1	482.4	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

(1) Watt-days/gram.

(2) All temperatures in °C.

(3) pou/hr-ft^2 . Example: 0.467E 06 = 0.467×10^6 .

(4) pou/hr-ft^3 . Example: 0.372E 08 = 0.372×10^8 .

(5) Watts/gram of core material (Th-235U).

FIGURE 16

EARLY ROTAX IEN DATA SHEET FOR Th-²³⁵U ASSEMBLY NO. TMT 1-3

Date:	8/31/64	Channel Effluent:	214.0 °C
Delta T:	28.4 °C	Surface Temp.:	260.6 °C
Flow:	152 gpm	Core Temperature:	496.4 °C
Inlet:	183.4 °C	Heat Flux:	450,402 pou/hr-ft ²
Power:	1.144 MW		

Layer	Power Shape (1)	Spec. Expos. (2)	Core Temp. (3)	Channel (3) Temperature		Surface (3) Temperature		Surface Heat Flux (4)		Volumetric Heat Generation (5)	Spec Power (6)
				Inner	Outer	Inner	Outer	Inner	Outer		
1	0.023	3.3	187.2	183.4	183.4	184.1	184.1	0.551E 04	0.509E 04	0.437E 06	0.7
2	0.090	13.2	198.3	183.5	183.5	186.4	186.2	0.218E 05	0.201E 05	0.172E 07	2.6
3	0.167	24.5	211.2	183.7	183.7	189.0	188.7	0.404E 05	0.373E 05	0.320E 07	4.8
4	0.259	38.1	226.7	184.0	184.0	192.3	191.8	0.627E 05	0.579E 05	0.497E 07	7.4
5	0.369	54.4	245.3	184.5	184.4	196.3	195.6	0.896E 05	0.827E 05	0.710E 07	10.6
6	0.508	73.9	267.4	185.1	185.0	201.2	200.3	0.122E 06	0.112E 06	0.963E 07	14.4
7	0.658	96.9	293.6	186.0	185.9	207.1	205.8	0.160E 06	0.147E 06	0.126E 08	18.9
8	0.841	123.9	324.1	187.2	186.9	214.1	212.5	0.204E 06	0.188E 06	0.162E 08	24.2
9	1.059	156.0	360.4	188.6	188.3	222.5	220.5	0.257E 06	0.237E 06	0.203E 08	30.5
10	1.333	196.4	405.4	190.4	190.0	233.1	230.5	0.323E 06	0.298E 06	0.256E 08	38.4
11	1.606	236.6	450.2	192.7	192.1	244.1	240.9	0.390E 06	0.360E 06	0.309E 08	46.3
12	1.777	261.7	479.1	195.3	194.6	252.2	248.5	0.431E 06	0.398E 06	0.341E 08	51.2
13	1.856	273.5	494.0	196.1	197.2	257.5	253.6	0.450E 06	0.416E 06	0.357E 08	53.5
14	1.855	273.2	496.4	200.9	199.9	260.3	256.2	0.450E 06	0.415E 06	0.356E 08	53.4
15	1.777	261.8	487.1	203.7	202.5	260.6	256.5	0.431E 06	0.398E 06	0.341E 08	51.2
16	1.630	240.1	466.6	206.3	205.0	258.5	254.3	0.395E 06	0.363E 06	0.313E 08	47.0
17	1.421	209.3	436.2	208.7	207.2	254.2	250.3	0.345E 06	0.318E 06	0.273E 08	40.9
18	1.163	171.3	397.6	210.7	209.0	247.9	244.4	0.282E 06	0.260E 06	0.223E 08	33.5
19	0.877	129.2	353.7	212.2	210.5	240.3	237.1	0.213E 06	0.196E 06	0.168E 08	25.3
20	0.586	86.4	308.1	213.3	211.6	232.1	229.4	0.142E 06	0.131E 06	0.113E 08	16.9
21	0.327	48.2	266.8	214.0	212.2	224.5	222.1	0.794E 05	0.733E 05	0.629E 07	9.4

(1) Dimensionless number representing axial power distribution.

(2) Watt-days/gram.

(3) All temperatures in °C.

(4) pou/hr-ft². Example: 0.551E 04 = 0.551 x 10⁴.(5) pou/hr-ft³. Example: 0.437E 06 = 0.437 x 10⁶.(6) Watts/gram of core material (Th-²³⁵U).

FIGURE 17

LAST ROTAX IEM DATA SHEET FOR Th-235U ASSEMBLY No. TWT 1-3

Date: 12/1/64 Channel Effluent: 214.3 °C
 Delta T: 30.3 °C Surface Temp: 253.9 °C
 Flow: 151 gpm Core Temperature: 465.3 °C
 Inlet: 181.6 °C Heat Flux: 405,345 pcu/hr-ft²
 Power: 1.812 MW

Layer	Power Shape (1)	Spec. (2) Exposure	Core (3) Temp	Channel Temperature (3)		Surface Temperature (3)		Surface Heat Flux (4)		Volumetric Heat Generation (5)	Spec. (6) Power
				Inner	Outer	Inner	Outer	Inner	Outer		
1	0.045	80.6	189.6	181.6	181.6	183.1	183.1	0.117E 05	0.108E 05	0.964E 06	1.4
2	0.176	315.8	218.7	181.8	181.8	187.8	187.5	0.454E 05	0.419E 05	0.359E 07	5.4
3	0.320	478.9	238.1	182.2	182.1	193.1	192.5	0.822E 05	0.759E 05	0.651E 07	9.8
4	0.479	881.8	258.3	182.8	182.8	198.2	198.3	0.123E 06	0.114E 06	0.975E 07	14.6
5	0.655	1227.5	297.3	183.8	183.6	206.1	204.8	0.168E 06	0.155E 06	0.133E 08	20.0
6	0.841	1612.0	330.3	185.0	184.8	213.7	212.0	0.216E 06	0.200E 06	0.171E 08	25.7
7	1.030	2026.4	363.6	186.5	186.2	221.6	219.5	0.265E 06	0.244E 06	0.210E 08	31.4
8	1.208	2449.8	395.3	188.3	187.9	229.6	227.0	0.311E 06	0.287E 06	0.246E 08	36.9
9	1.366	2848.5	423.6	190.4	189.9	237.1	234.1	0.351E 06	0.324E 06	0.278E 08	41.7
10	1.496	3180.8	447.7	192.8	192.1	243.9	240.6	0.385E 06	0.356E 06	0.305E 08	45.7
11	1.564	3398.1	461.0	193.3	194.5	248.7	245.1	0.402E 06	0.371E 06	0.319E 08	47.8
12	1.576	3488.9	465.3	197.9	196.9	251.6	247.9	0.403E 06	0.374E 06	0.321E 08	48.1
13	1.551	3471.2	463.4	200.4	199.3	253.3	249.5	0.399E 06	0.368E 06	0.316E 08	47.3
14	1.495	3360.2	456.6	202.9	201.6	253.9	250.0	0.384E 06	0.355E 06	0.304E 08	45.6
15	1.411	3182.9	444.9	203.3	203.9	253.4	249.5	0.363E 06	0.335E 06	0.287E 08	43.1
16	1.296	2880.9	427.8	207.5	205.9	251.7	247.9	0.333E 06	0.307E 06	0.264E 08	39.6
17	1.146	2516.5	404.8	209.5	207.8	248.6	244.9	0.293E 06	0.272E 06	0.233E 08	35.0
18	0.961	2078.0	375.3	211.2	209.4	244.0	240.5	0.247E 06	0.228E 06	0.196E 08	29.3
19	0.745	1586.7	340.2	212.6	210.8	238.0	234.9	0.192E 06	0.177E 06	0.152E 08	22.8
20	0.513	1075.8	301.5	213.6	211.7	231.1	228.3	0.132E 06	0.122E 06	0.104E 08	15.7
21	0.293	607.9	264.3	214.3	212.3	224.3	221.8	0.753E 05	0.695E 05	0.596E 07	8.9

(1) Dimensionless number representing axial power distribution.

(2) Watt-days/gram.

(3) All temperatures in °C.

(4) pcu/hr-ft². Example: 0.117E 05 = 0.117 X 10⁵.(5) pcu/hr-ft³. Example: 0.924E 06 = 0.924 X 10⁶.

(6) Watts/gram of core material (Th-235U).

FIGURE 18

TIME-WEIGHTED AVERAGE VALUES FOR Th-²³⁵U ASSEMBLY NO. TMT 1-3

Layer	Core Temp. (°C)	Surface Temperature (°C)		Surface Heat Flux ⁽¹⁾		Specific Power ⁽²⁾
		(Inner)	(Outer)	(Inner)	(Outer)	
1	188.3	183.1	183.1	0.930E 04	0.868E 04	1.1
2	206.5	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	0.386E 06	0.358E 06	46.0
15	444.9	252.3	248.5	0.363E 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	226.7	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

(1) pou/hr-ft^2 . Example: 0.930E 04 = 0.930×10^4 .

(2) Watts/gram of core material (Th-²³⁵U).

FIGURE 19

VARIABLES VERSUS SPECIFIC EXPOSURE FOR HOTTEST REGION OF
Th-235U ASSEMBLY NO. TMT 1-3

Layer 13 (76 inches from top of tube)

Spec. (1) Expos.	Core Temp. (2)	Channel Temperature (2)		Surface Temperature (2)		Surface Heat Flux (3)		Volumetric Heat Generation (4)	Spec. Power (5)
		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	252.6	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
1558.2	453.0	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	416.9	194.2	193.4	239.1	236.0	0.339E 06	0.313E 06	0.268E 08	40.8
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

(1) Watt-days/gram.

(2) All temperatures in °C.

(3) pou/hr-ft^2 . Example: $0.450E 06 = 0.450 \times 10^6$.

(4) pou/hr-ft^3 . Example: $0.357E 08 = 0.357 \times 10^8$.

(5) Watts/gram of core material (Th-235U).

FIGURE 20
ROTAM INPUT DATA

	<u>ASSEMBLY</u> <u>TMT 1-2</u>		<u>ASSEMBLY</u> <u>TMT 1-3</u>	
Outer Housing, ID (inches)	2.900		2.900	
Outer Housing Rib Size, 4 ribs (inches)	0.125 X 0.152		0.125 X 0.152	
Inner Housing, OD (inches)	1.424		1.424	
Inner Housing Rib Size, 4 ribs (inches)	0.060 X 0.188		0.060 X 0.188	
Fuel Tube - Clad OD (inches)	2.538		2.540	
Core OD (inches)	2.478		2.480	
Core ID (inches)	1.902		1.900	
Clad ID (inches)	1.842		1.840	
Core Length (inches)	97.92		97.92	
Coolant Channels	<u>(Inner)</u>	<u>(Outer)</u>	<u>(Inner)</u>	<u>(Outer)</u>
Heat split	0.44	0.56	0.44	0.56
Flow split	0.408	0.592	0.408	0.592
Velocity constant	0.313	0.218	0.314	0.2197
Equivalent channel width (inches)	0.349	0.321	0.347	0.319
Fuel Surfaces				
Heat split	0.44	0.56	0.44	0.56
Area (square feet)	3.93	5.42	3.93	5.42
Clad thickness (feet)	0.0025	0.0025	0.0025	0.0025
Fuel Pieces				
Heat split	1.0		1.0	
Core volume (cubic feet)	0.1122		0.1128	
Core thickness (feet)	0.024		0.0241	
Weight (tonnes)	0.03960		0.03971	

FIGURE 21
FUEL EXPOSURE INTERVALS IN HWCTR

<u>Real Time</u> <u>Interval</u>	<u>Date</u>	<u>Reactor</u> <u>Differential</u> <u>Exposure</u> <u>(MWD)</u>	<u>Power</u> <u>(MW)</u>	<u>Equivalent</u> <u>Time</u> <u>Interval</u> <u>(days)</u>	<u>HWCTR</u> <u>Cycle</u>
(1964)					
8/25 - 8/31	8/31	241.27	49.58	4.87	H-2.5 ↓
9/1 - 9/5	9/5	211.40	50.23	4.21	
9/5 - 9/9	9/9	211.40	50.57	4.18	
9/15 - 9/19	9/19	204.40	49.33	4.14	
9/20 - 9/24	9/24	207.00	50.16	4.13	
9/24 - 9/28	9/28	207.00	51.50	4.02	
9/28 - 9/30	9/30	131.77	52.89	2.49	
10/1 - 10/3	10/3	64.37	50.49	1.27	
10/3 - 10/7	10/7	196.13	50.74	3.87	
10/8 - 10/12	10/12	154.74	51.25	3.02	
10/13 - 10/16	10/16	92.55	50.81	1.82	H-2.6 ↓
10/16 - 10/19	10/19	166.00	51.21	3.24	
10/19 - 10/22	10/22	166.00	51.41	3.23	
10/22 - 10/26	10/26	177.84	51.51	3.45	
10/26 - 10/29	10/29	177.84	54.46	3.27	
10/29 - 10/31	10/31	85.13	54.36	1.57	
11/10 - 11/18	11/17	283.75	44.04	6.44	
11/18 - 11/23	11/23	269.00	55.08	4.88	
11/23 - 11/25	11/25	66.30	55.24	1.20	
11/26 - 12/1	12/1	234.08	55.51	4.22	

REACTOR LOCATION

TMT 1-2 in Position 40

TMT 1-3 in Position 37

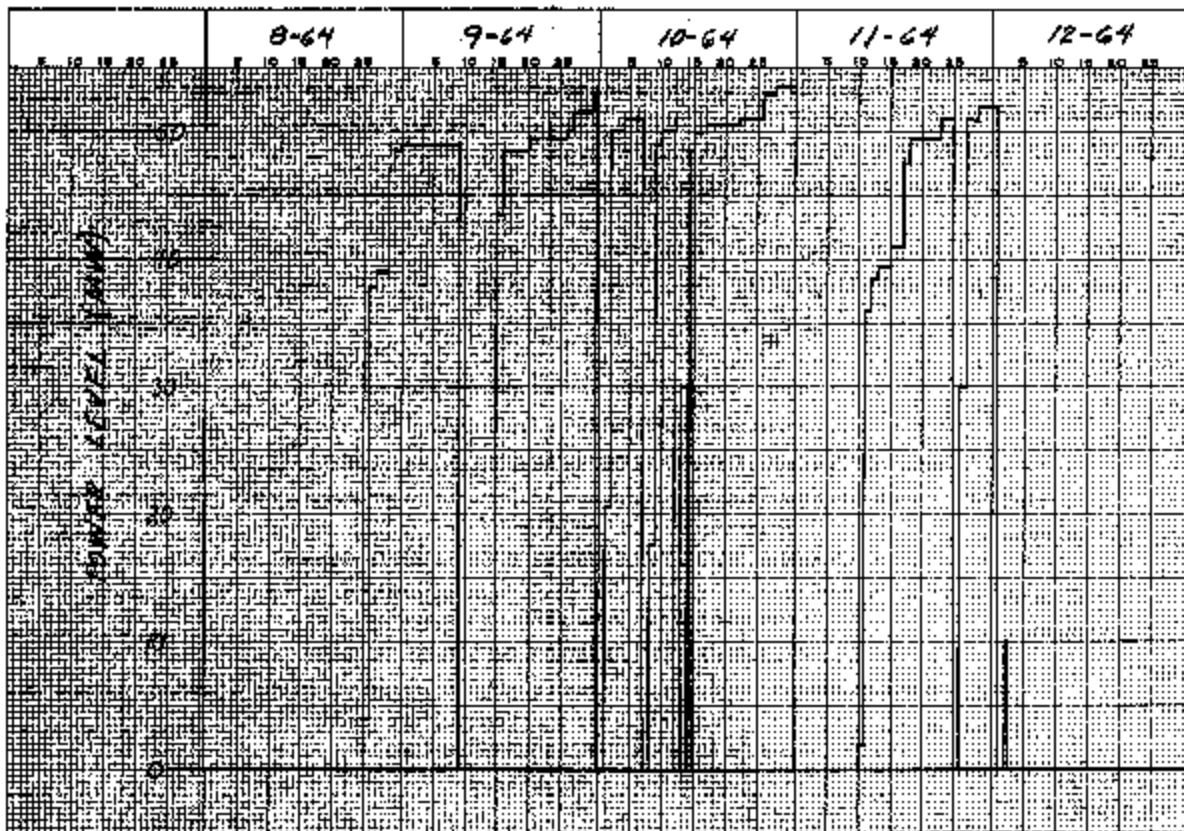


FIGURE 22 KWCTR POWER LEVELS DURING IRRADIATION OF Th-²³⁵U FUEL ASSEMBLIES

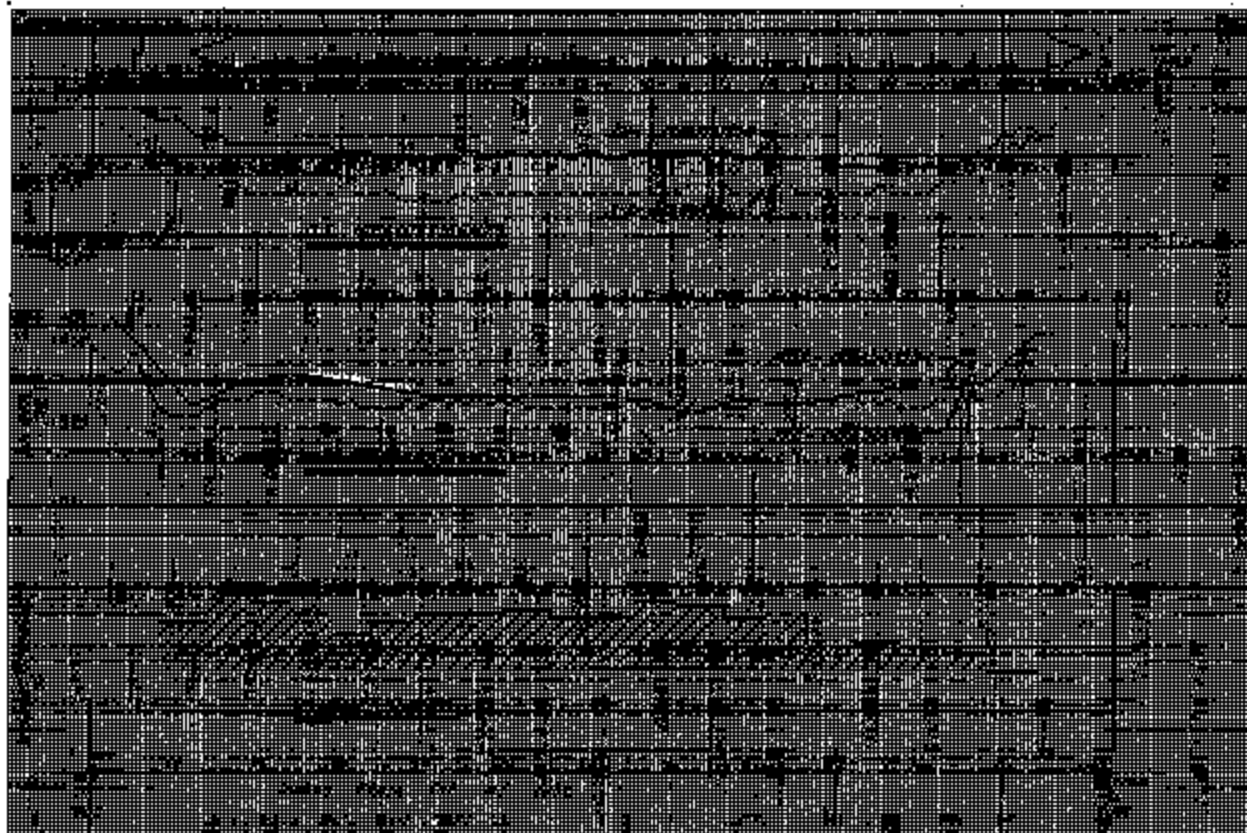


FIGURE 24 THE 4 PROPORTIONATE REPRESENTATION OF THE 13th FIVE YEAR No. 1 (ANNUAL 1961-2)