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AEC RESEARCH AND DEVELOPMENT REPORT

# METAL FUEL TUBE MANUFACTURE

S. R. Nemeth



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*Aiken, South Carolina*

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## ABSTRACT

Development and fabrication of tubular coextruded Zircaloy-clad uranium metal fuel elements for a heavy water-moderated-and-cooled power reactor is described. Approximately 200 experimental uranium tubular elements, 10 feet long, were fabricated of which 36 were irradiated. The remainder were used for evaluation of fabrication techniques and flow tests. Although the majority of tubes had cores of unalloyed uranium, uranium alloys with 2 w/o Zr and with Fe, Si, Al and Mo (approximately 0.2% total) were also included. Some 24 short-length (12-inch) elements were fabricated using brazed end seals rather than the integral end seals used for the long tubes. Fabrication techniques were developed for manufacture of 80 Zircaloy-clad Zr-$^{235}$U alloy tubular driver elements, 10 feet long, for the HWCTR. Utilizing the techniques developed for uranium fuel tubes, a number of Th-$^{235}$U metal fuel tubes were coextruded to pilot the manufacture of Th-$^{233}$U breeder reactor fuel.

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# METAL FUEL TUBE MANUFACTURE

## INTRODUCTION

Metallic uranium fuel elements for heavy water-moderated-and-cooled power reactors have several advantages over oxide fuel. Among these are higher nuclear reactivity, higher thermal conductivity and potentially lower fabrication cost. A development effort for fabrication of tubular metallic fuel elements was successfully undertaken at Nuclear Metals, West Concord, Mass. Approximately 200 experimental uranium tubular elements were fabricated during the period 1957 to 1964. In addition, approximately 80 zirconium-$^{235}$uranium alloy tubular fuel elements were fabricated for use as drivers for the HWCTR in which the metal test fuel was irradiated. This report summarizes the fabrication development effort on these various fuel tubes and reference documents that contain more detailed information.

## SUMMARY

Coextruded Zircaloy-clad uranium-core tubular elements were investigated as potential fuels for use in heavy water-moderated-and-cooled power reactors. Nuclear Metals conducted the development work for fabrication of coextruded metal power fuel[1].

Zircaloy was used as the cladding material because of its low absorption cross section for neutrons, excellent corrosion resistance to water, and its high degree of metallurgical compatibility with uranium. This program included elements in which the core material was unalloyed uranium, uranium-2 w/o zirconium, and other uranium alloys with Fe, Si, Al, and Mo.

(1) TID-7545, "Fuel Elements Conference, Paris,", November 18-23, 1957, pages 157-181.

In order to increase the power output per fuel assembly, the original thick-wall fuel tube (0.297" thick) was reduced to 0.180" and a two-tube concentric fuel element designed. The thinner wall not only allowed a greater power output but also reduced the fuel temperature and resulted in a lower level of cladding strain for the same percentage core volume change during irradiation. Following the fabrication of a series of experimental tubes, a set of fifteen inner and outer full-length fuel tubes was made for test irradiation.

While the bulk of the fuel tubes were approximately 120 inches in length for use in the HWCTR, some tubes were 44 inches in length for use in the VBWR. The long tubes were all fabricated with integral end seals. A number of short-length (about 12") experimental tubes were fabricated having brazed end seals. These short tubes provided means for irradiating a wider range of compositions and/or heat treatment in a minimum of reactor positions, as well as expediting postirradiation examination.

Fabrication techniques for manufacture of 10-foot long Zircaloy-clad zirconium-$^{235}$uranium alloy tubular driver elements were developed for the HWCTR. Three full complements of tubes (24 per set) were fabricated and two sets of tubes were irradiated.

In connection with studies of heavy water-moderated-and-cooled Th-$^{233}$U breeder reactors, a program was successfully undertaken to fabricate two pile-worthy Zircaloy-clad Th-1.4 w/o $^{235}$U tubular elements which were later irradiated in the HWCTR.

A tabulation of the power program fuel tubes is presented at the end of this report; more complete details of each group of tubes are presented in Appendix A. Irradiation test data will be reported in a supplement to this report.

## DISCUSSION

During the initial phases of the Du Pont study of power reactors, a heavy water-moderated-and-cooled 100 MWe (net electrical) reactor was contemplated. The Heavy Water Components Test Reactor (HWCTR) of 60 MW(th) capacity was constructed for the purpose of testing the fuel alloys and assembly arrangements then visualized. The primary fuel element for the 100 MWe power reactor was considered to be a Zircaloy-2-clad metal tubular design with a natural uranium-2 w/o zirconium core. The dimensions of this tube were 2.060" OD X 1.467" ID with a core length of about 10 feet for the components testing reactor and 15 feet for a full-scale reactor.

Under full-power operating conditions the maximum temperatures to which the tubular fuel elements were expected to be subjected were 295°C for cladding surface and 500°C for central core metal. Heat flux was expected to be approximately 400,000 pcu/sq.ft/hr with a maximum coolant temperature of 230°C. Fuel elements were designed to be in a vertical position centered in ribbed Zircaloy-2 housing tubes with 0.400" cooling annuli. Initially, average exposure was estimated at 3000 MWD/tonne; it was raised later to a goal of 10,000 MWD/tonne.

The tubular metal fuel elements were fabricated by a coextrusion process with the fabrication development being done by Nuclear Metals. Preliminary production cost estimates on making 600 15-foot tubes per year (approximately 2 reactor charges) were $25/lb of uranium with about half the cost being for the Zircaloy. The experimental tube cost was in the range of $80 to $100/lb of uranium, the high cost resulting primarily from inclusion of development costs.

The coextrusion process used for making the tubes consisted of the extrusion of a cylindrical billet, containing prefabricated core and cladding components, into a tubular shape. The extrusion was carried out at an elevated temperature (600 to 650°C). Conical extrusion dies were used so that both the core and cladding components could be made to flow in a streamlined fashion resulting in uniform core and cladding throughout the length of the tube. Particular care was taken in the shape of the billet components to prevent nonuniform cladding of the tube ends.

Individual billet components were made by conventional metal-working techniques. The core was made by either extrusion or casting followed by machining to finished size. Cladding sleeves were machined from extruded Zircaloy stock and the end seals machined from Zircaloy forgings. The billet components were assembled and encased in copper which acted as a lubricant during the high-temperature extrusion.

The coextruded tube was heat treated in its copper extrusion jacket. After heat treatment, the copper was removed by acid dissolution from the Zircaloy cladding surface. Following inspection, the tube was etched and then autoclaved in high-temperature water (395 °C) and high pressure steam (1500 psi at 400 °C). Various in-process nondestructive tests were employed to insure core-to-clad bond quality and clad thickness.

The general types of tubes fabricated are described below. More complete details for individual experimental tubes are presented in the tabulated summary of power program fuel tubes and in Appendix A.

A. Thick-Wall Tubes

The original design for metal tubular power fuel elements was for a 2.060" OD X 0.297" wall including 0.015" thick cladding. The tubes were approximately 10 feet long for the HWCTR, 4 feet for VBWR, and 15 feet for the contemplated 100 MWe power reactor. The tube wall thickness was based on an expected 500 to 550 °C maximum central metal temperature, a heat flux of about 400,000 pcu/ft$^2$-hr, and a burnup to 3000 MWD/tonne.

Uranium-2 w/o zirconium was the first choice for a core alloy because of its good extrusion compatibility with Zircaloy-2 cladding. This alloy was reported to exhibit a lower corrosion rate in high temperature water than unalloyed uranium, an advantage in the event of cladding failure in the reactor. In addition, the irradiation

stability was expected to be as good as or better than that of unalloyed uranium. A total of 42 U-2 w/o Zr tubes were fabricated, 10 of which were the 4-foot tubes for VBWR. Seven full-length tubes and one short tube were irradiated at SRP, one full-length tube at NRU and one short tube at VBWR.

Postirradiation inspection revealed that splitting or cracking had occurred in some cores during irradiation. As a result, the core material in subsequent tubes was changed to unalloyed uranium, and studies were begun on other uranium alloys.

The Zircaloy cladding thickness was increased from 0.015" to 0.030" for the unalloyed uranium tubes so that the uranium content of the tubes would not be increased. Secondarily, the thicker cladding gave more adequate insurance of obtaining satisfactory tubes despite the greater difference in fabrication properties of unalloyed uranium and the Zircaloy-2 cladding and end seals.

Thirteen thick-wall tubes with unalloyed uranium cores, one with U-1 w/o Si core and one with U-1.5 w/o Mo core were fabricated before the fuel design was changed to include thinner wall thickness. Reduction in wall thickness would reduce the maximum central core temperatures and, hopefully, increase exposures to higher levels than those originally specified. Two unalloyed uranium tubes were irradiated prior to adoption of the change.

Fabrication details for the thick-wall tubes are presented in Appendix A, Sections 1-6, 8 and 10-13.

B. Thin-Wall Tubes

In early 1960 the single-tube, thick-wall fuel design was changed to a concentric two-tube design having thin walls. The following table compares the dimensions of the concentric tubes with the single thick-wall tube.

| Item | Single Tube (inches) | Concentric Tubes Outer (inches) | Concentric Tubes Inner (inches) |
|---|---|---|---|
| Outside diameter | 2.060 | 2.060 | 1.020 |
| Inside diameter | 1.462 | 1.700 | 0.660 |
| Cladding thickness | 0.030 | 0.025 | 0.025 |
| Core thickness | 0.237 | 0.130 | 0.130 |
| Total wall thickness | 0.299 | 0.180 | 0.180 |

Development and fabrication of the outer and inner thin-wall fuel elements was performed concurrently.

1. Outer Tubes

Of the 55 experimental thin-wall outer tubes fabricated, 44 had unalloyed uranium cores. Five of the 55 tubes had enriched uranium cores; two unalloyed full-length tubes were enriched to 2.1% $^{235}U$ for irradiation in HWCTR; and three alloyed short tubes were enriched to 3.0% $^{235}U$ for irradiation in VBWR. The tubes with uranium alloy cores included four with U-1 w/o Si (one with U enriched to 3% $^{235}U$); six with U-1.5 w/o Mo (two with U enriched to 3% $^{235}U$); and one with U-0.3 w/o Al-0.5 w/o Si.

Four of the unalloyed uranium tubes were fabricated with different clad thicknesses to evaluate (1) the effect of cladding restraint on fuel swelling during irradiation and (2) whether the direction of swelling could be controlled. Dimensions of these tubes are listed below.

| | Normal Tube (inches) | "Restraint" Tubes Type A (inches) | Type B (inches) | Type C (inches) |
|---|---|---|---|---|
| Outside diameter | 2.060 | 2.060 | 2.060 | 2.060 |
| Inside diameter | 1.700 | 1.560 | 1.670 | 1.670 |
| Cladding thickness, outside | 0.025 | 0.060 | 0.025 | 0.040 |
| Cladding thickness, inside | 0.025 | 0.060 | 0.040 | 0.025 |
| Core thickness | 0.130 | 0.130 | 0.130 | 0.130 |
| Total wall thickness | 0.180 | 0.250 | 0.195 | 0.195 |

Among the developments accomplished with the experimental tubes were the establishment of basic information for fabrication of the thin-wall tubes, such as methods for grain refinement of the billet core prior to machining and billet preshape design which resulted in obtaining more uniform cladding of the coextruded tubes. The process developed for grain refinement of the billet core consisted of beta treatment of the core stock followed by a single extrusion at a low reduction ratio. This replaced the one initially used which consisted of repeated alpha extrusions with intermediate upsets and which resulted in low metal yields due to the large amount of machining involved. A billet end shape ("preshape") which incorporated several different tapers was found to result in more uniform cladding thickness in the taper region between the core and end cap of the extruded tubes than did spherical preshapes.

Six of the outer tubes were irradiated individually. These included two unalloyed natural uranium tubes, two unalloyed uranium with 2.1 % $^{235}U$ enrichment, one Type A restraint tube, and one short U-1.5 w/o Mo tube enriched to 3.0 % $^{235}U$ (assembly poisoned to some degree; tube originally scheduled for VBWR).

Fabrication details for the thin-wall outer tubes are presented in Appendix A, Sections 14-16, 18-19, 21-22, 24-25 and 27-28.

2. Inner Tubes

Twenty-one experimental thin-wall inner tubes were fabricated, all with unalloyed uranium cores. Five were enriched to 2.1 % $^{235}U$. Three were fabricated with different cladding thicknesses to evaluate the effect of cladding restraint, as was done for the outer tubes. Dimensions of these tubes are listed below.

| | Normal Tube (inches) | Restraint Tubes Type D (inches) | Restraint Tubes Type E (inches) |
|---|---|---|---|
| Outside diameter | 1.020 | 1.020 | 1.020 |
| Inside diameter | 0.660 | 0.520 | 0.630 |
| Cladding thickness, outside | 0.025 | 0.060 | 0.040 |
| Cladding thickness, inside | 0.025 | 0.060 | 0.025 |
| Core thickness | 0.130 | 0.130 | 0.130 |
| Total wall thickness | 0.180 | 0.250 | 0.195 |

Four of the unalloyed, natural uranium, inner, thin-wall tubes were irradiated individually. The process for fabricating the inner tubes was similar to that for the outer tubes.

Details are presented in Appendix A, Sections 17, 20, 23 and 26.

3. Semi-Production Run

Fifteen sets of unalloyed, natural uranium, thin-wall tubes were successfully fabricated for irradiation as nested pairs in HWCTR. These tubes were made using the fabrication techniques developed for making the individual outer and inner experimental thin-wall tubes. Seven fuel assemblies using seven each of these tubes were irradiated in HWCTR with Zircaloy-2 spiral ribbon-type spacers between the two fuel tubes. Irradiation testing of these tubes was terminated following early failure of two assemblies as a result of rapid fretting corrosion of the Zircaloy cladding where the spacers had vibrated against the tube walls.

Fabrication details for these tubes are presented in Appendix A, Sections 34 and 35.

C. Short Metal Tubes

A short length ($11\frac{1}{4}$") tubular fuel element with brazed end seals was designed to provide a means for irradiating a wide range of compositions and/or heat treatments in a minimum number of reactor positions. Postirradiation examination was expedited by the use of short tubes because they could be introduced into high level caves directly and without the cutting and handling required for long elements. The core wall thickness of these tubes was approximately 40% greater than the previous thin-wall design to obtain a higher core temperature during irradiation. Twenty-four short

elements, consisting of four variations of core heat treatment and composition, were fabricated from the long extruded tubes.

| Tube Numbers | Composition |
|---|---|
| 150,151 | Unalloyed uranium |
| 152,153, 154 | U-350 ppm Fe-900 ppm Al |
| 155 | U-350 ppm Fe-900 ppm Al-500 ppm Si-1000 ppm Mo |
| 157,158 | U-350 ppm Fe-900 ppm Al-300 ppm Si |

| Tube Numbers | Billet Core Heat Treatment Prior to Extrusion Cladding |
|---|---|
| 150,151 | Triple beta-treated followed by series of extrusions and intermediate upsets. |
| 152,153, 155,157, 158 | Beta-treated - air-cooled followed by beta-treated - oil quench. |
| 154 | Gamma-treated - furnace-cooled. |

Two reactor assemblies containing a total of five short tubes from each of Nos. 153, 154 and 158 for a total of fifteen short tubes were irradiated in the HWCTR. Fabrication details for these tubes are presented in Appendix A, Section 29.

D. Thorium Metal Tubes

The Du Pont program on power reactor development included the assessment of the heavy water-moderated-and-cooled breeder reactor concept operating on the Th-$^{233}$U fuel cycle. Fabrication of several Th-$^{235}$U alloy fuel elements was undertaken as a step in the evaluation of a prototype fuel element. The coextruded test elements, 2.540" OD X

1.830" ID, 0.290" thick core and 0.030" cladding thickness, were designed for a series of irradiations in HWCTR. Four thorium-natural uranium and three thorium-enriched uranium elements were made. Two of the enriched elements were irradiated in the HWCTR. Fabrication details for these tubes are presented in Appendix A, Section 33.

E. HWCTR Driver Tubes

1. M-1 and M-2 Driver Tubes

Eight prototype tubular driver elements were made with natural uranium to develop the process for fabricating enriched tubes for HWCTR. After successful development, three enriched tubes were fabricated, two of which were for test irradiation at SRP. To produce 50 acceptable tubes for HWCTR, a production run of 56 tubes was made.

All tubes had zirconium-9.3 w/o fully enriched uranium cores with Zircaloy-2 end seals. Twenty-seven tubes were clad with Zircaloy-2, twenty-seven with Zircaloy-4,(1) and two with Zircaloy-2 on the outer surface and Zircaloy-4 on the inner surface. The change to Zircaloy-4 was made midway during fabrication in view of an expected lesser amount of hydrogen absorbed during irradiation by Zircaloy-4 as compared to Zircaloy-2. Nominal dimensions of the tubes were 2.300" OD X 0.167" wall including 0.015" cladding thickness.

Of the 56 production elements only 3 were not considered of irradiation quality because of minor cladding defects.

(1) Current designation of this alloy is low nickel-Zircaloy-2.

Forty-eight of the tubes were irradiated in HWCTR, 24 as the M-1 driver set and 24 as the M-2 driver set, with satisfactory results. The remaining 8 enriched tubes, including the 3 with minor cladding defects, were placed in storage at SRP.

Fabrication details for these tubes are presented in Appendix A, Sections 7, 9 and 36.

2. Two-Tube Concentric Design

To permit operation of the HWCTR at higher flux levels in test fuel positions, a concentric two-tube driver fuel design was developed. The two-tube nested design provided greater heat transfer area than was available in the one-tube case. The uranium loading per driver assembly was also increased from 108 grams/ft to 120 grams/ft. Four outer and five inner prototype tubes were fabricated. Comparison of the dimensions of these tubes to the single-tube design follows:

| | Single Tube | Concentric Tubes | |
|---|---|---|---|
| | | Outer | Inner* |
| Outside diameter, inches | 2.300 | 2.700 | 1.720 |
| Inside diameter, inches | 1.966 | 2.430 | 1.400 |
| Cladding thickness, mils | 15 | 15 | 15 |
| Core thickness, mils | 137 | 105 | 130 |
| Total wall thickness, mils | 167 | 135 | 160 |

* Four inner tube external ribs, equally spaced 0.040" high X 0.060" wide, were provided. (These shallow ribs were used as a base for attachment of full-height ribs by electron beam welding.)

The core alloy was changed from zirconium-9.3 w/o enriched uranium to Zircaloy-2 6.5 w/o enriched uranium.

The lower uranium concentration was used to utilize core thicknesses in the range in which prior experience was available; the new development costs incident to the use of thinner walls of 9.3 w/o uranium were thus avoided.

The inner tube, originally conceived with a smooth outer surface, was modified to incorporate shallow Zircaloy ribs on this surface to provide a suitable base for subsequent electron beam welding of full-height Zircaloy ribs for spacing the concentric tubes. Electron beam welding of the full-height ribs to the extruded shallow ribs was satisfactorily demonstrated on a 70-inch length of a prototype inner tube.

Development was terminated on the two-tube driver design because the higher cost of producing elements of this type did not appear to be justified by their difference in performance over that of single-tube drivers.

Fabrication details of the two-tube design are presented in Appendix A, Sections 30 and 31.

3. M-3 Driver Tubes

To maintain the reactivity characteristics of the two-tube design, the entire uranium loading of the inner tube was added to that of the outer tube. To attain the desired higher flux in the test positions, it was necessary to reduce the coolant water temperature

to permit a higher burnout safety factor and hence higher heat transfer rate of the driver tubes.

Prior to fabricating the 28 Zircaloy-2 11.1 w/o fully enriched uranium driver tubes, 3 prototypes were made using natural uranium. The design of this element is externally identical to the outer tube of the two-tube driver element described above. The uranium in the core alloy was increased, placing in this single tube all the uranium that was originally distributed between the two tubes of the earlier design.

Four of the 28 production tubes were not considered irradiation candidates because of minor defects. Operation of the HWCTR was terminated before any of this set of driver tubes could be irradiated.

Fabrication details are presented in Appendix A, Sections 32 and 37.

## NUCLEAR METALS

### Power Reactor Program Progress Reports

| | | | |
|---|---|---|---|
| NMI-4350 | 5/30/57 - 6/23/57 | NMI-7228 | 5/1/60 - 5/31/60 |
| 4351 | 6/24/57 - 7/19/57 | 7229 | 6/1/60 - 6/30/60 |
| 4353 | 7/20/57 - 8/20/57 | 7230 | 7/1/60 - 7/31/60 |
| 4354 | 8/21/57 - 9/20/57 | 7231 | 8/1/60 - 8/31/60 |
| 4355 | 9/21/57 -10/16/57 | 7232 | 9/1/60 - 9/30/60 |
| NMI-4356 | 10/17/57 - 11/17/57 | NMI-7233 | 10/1/60 - 10/31/60 |
| 4357 | 11/18/57 - 1/25/58 | 7234 | 11/1/60 - 11/30/60 |
| 4358 | 1/26/58 - 2/20/58 | 7235 | 12/1/60 - 12/31/60 |
| 4359 | 2/21/58 - 3/18/58 | 7236 | 1/1/61 - 1/31/61 |
| 4361 | 3/19/58 - 4/11/58 | 7237 | 2/1/61 - 2/28/61 |
| NMI-4362 | 4/12/58 - 5/6/58 | NMI-7238 | 3/1/61 - 3/31/61 |
| 4363 | 5/7/58 - 6/6/58 | 7239 | 4/1/61 - 4/30/61 |
| 4366 | 6/7/58 - 7/6/58 | 7240 | 5/1/61 - 5/31/61 |
| 4368 | 7/6/58 - 7/31/58 | 7241 | 6/1/61 - 7/31/61 |
| 4369 | 8/1/58 - 8/31/58 | 7242 | 8/1/61 - 8/31/61 |
| NMI-4381 | 9/1/58 - 9/30/58 | NMI-7243 | 9/1/61 - 9/30/61 |
| 4382 | 10/1/58 -10/31/58 | 7244 | 10/1/61 - 10/31/61 |
| 4383 | 11/1/58 -11/30/58 | 7245 | 11/1/61 - 11/30/61 |
| 4384 | 12/1/58 -12/31/58 | 7246 | 12/1/61 - 12/31/61 |
| 4385 | 1/1/59 - 1/31/59 | 7247 | 1/1/62 - 1/31/62 |
| NMI-4386 | 2/1/59 - 2/28/59 | NMI-7248 | 2/1/62 - 2/28/62 |
| 4392 | 3/1/59 - 3/31/59 | 7249 | 3/1/62 - 3/31/62 |
| 4393 | 4/1/59 - 4/30/59 | 7250 | 4/1/62 - 4/30/62 |
| 4394 | 5/1/59 - 5/31/59 | 7251 | 5/1/62 - 5/31/62 |
| 4395 | 6/1/59 - 6/30/59 | 7252 | 6/1/62 - 6/30/62 |
| NMI-4396 | 7/1/59 - 7/31/59 | NMI-7253 | 7/1/62 - 7/31/62 |
| 4397 | 8/1/59 - 8/31/59 | 7254 | 8/1/62 - 8/31/62 |
| 4398 | 9/1/59 - 9/30/59 | 7255 | 9/1/62 - 9/30/62 |
| 7221 | 10/1/59 -10/31/59 | 7256 | 10/1/62 - 10/31/62 |
| 7222 | 11/1/59 -11/30/59 | 7257 | 11/1/62 - 11/30/62 |
| NMI-7223 | 12/1/59 -12/31/59 | NMI-7258 | 12/1/62 - 12/31/62 |
| 7224 | 1/1/60 - 1/31/60 | 7259 | 1/1/63 - 1/31/63 |
| 7225 | 2/1/60 - 2/29/60 | 7260 | 2/1/63 - 4/30/63 |
| 7226 | 3/1/60 - 3/31/60 | | |
| 7227 | 4/1/60 - 4/30/60 | | |

## SUMMARY OF NUCLEAR METALS POWER PROGRAM FUEL TUBES

| NM Tube Nbr. | Composition | Description | Irrad. Assy. Number | Extruder and Date | NM Extru. Number | Status[1] and Location | Ref.[2] Info. | Autoclave Test Completion | Comments |
|---|---|---|---|---|---|---|---|---|---|
| 1 | U-2 w/o Zr | Thick wall | -- | Revere[3] 10/1/57 | None | Scrapped | 1 | None | Not extruded. Copper can torn off because not centered in liner. Disassembled. |
| 2 | U-2 w/o Zr | Thick wall | -- | Revere 10/1/57 | 15778 | Cut up | 1 | None | Tandem extrusion of 3 cores. Interface design varied. Destructive examined. |
| 3 | U-2 w/o Zr | Thick wall | -- | Revere 10/1/57 | 15777 | Cut up | 1 | None | Changes in interface design. Destructively examined. |
| 4 | U-2 w/o Zr | Thick wall | -- | Revere 10/29/57 | 15991 | Cut up | 2 | 3/18/58 | Used for etching experiments. Samples used for 800 °C heat treatment studies[4]. |
| 5 | U-2 w/o Zr | Thick wall | -- | Revere 10/29/57 | 15992 | Stored SRL | 2 | None | Used for SRL flow studies and HWCTR zero power tests. Not suitable for irradiation. |
| 6 | U-2 w/o Zr | Thick wall | -- | Revere 10/29/57 | 15993 | Cut up | 2 | None | First double evacuated and sealed billet. Destructively examined. |
| 7 | U-2 w/o Zr | Thick wall | -- | Revere 10/29/57 | 15994 | Cut up | 2 | None | First full scale 880 °C heat treatment. Two feet used for burst tests; one foot used for X-ray orientation studies at SRL; remainder used for corrosion tests. |
| 8 | U-2 w/o Zr | Thick wall | -- | Revere 10/29/57 | 15995 | Stored SRL | 2 | None | Used for NRU flow tests at SRL and HWCTR zero power tests. Not suitable for irradiation. |
| 9 | U-2 w/o Zr | Thick wall | -- | Revere 10/29/57 | 15996 | Cut up | 2 | None | Tandem extrusion of 3 cores. All 3 sections used for vertical heat treatment and corrosion studies. |
| 10 | U-2 w/o Zr | Thick wall | -- | Revere 12/19/57 | 16240 | Cut up | 3 | Failed 7/31/58 | Zr picked up on die during extrusion. Rear cladding thin. Heat treated on graphite cylinder. Failed during autoclave test. Repaired and heat treated on Mo pads with no restraint. Used for metallurgical structure studies. |
| 11 | U-2 w/o Zr | Thick wall | SPR-6[5] | Revere 12/19/57 | 16241 | Irradiated SRP | 3 | 3/31/58 | Heat treated at 800 °C |
| 12 | U-2 w/o Zr | Thick wall | -- | Revere 12/19/57 | 16242 | Cut up | 3 | None | Heat treated on tantalum pad. Used for corrosion studies. |
| 13 | U-2 w/o Zr | Thick wall | -- | Revere 12/19/57 | 16243 | Cut up | 3 | None | Rear cladding thin. Nail hole over core 5 mils deep. Heat treated on stainless steel pad. Used for corrosion studies. |

(1) Tube status as of 3/1/65.

(2) Reference Information is presented in Appendix A, listed under appropriate section number.

(3) Revere Copper & Brass Co., Detroit, Michigan.

(4) Unless otherwise specified, heat treatment of U-2 w/o Zr tubes was 880 °C for 8 hours followed by cooling at a rate equivalent to air cooling.

(5) SPR - Savannah Production Reactor Test Fuel number.

## Summary of Nuclear Metals Power Program Fuel Tubes (Continued)

| NM Tube Nbr. | Composition | Description | Irrad. Assy. Number | Extruder and Date | NM Extru. Number | Status and Location | Ref. Info. | Autoclave Test Completion | Comments |
|---|---|---|---|---|---|---|---|---|---|
| 14 | U-2 w/o Zr | Thick wall | -- | Revere 12/19/57 | 16244 | Stored SRL | 3 | 3/26/58 | Tantalum pits on surface. Used for HWCTR zero power tests. May be suitable for irradiation; however, warping did occur during autoclaving and may be expected to warp if irradiated. |
| 15 | U-2 w/o Zr | Thick wall | SPR-2 | Revere 1/30/58 | 16431 | Irradiated SRP | 3 | 3/28/58 | None. |
| 16 | U-2 w/o Zr | Thick wall | -- | Revere 1/30/58 | 16432 | Stored SRL | 3 | 10/28/58 | Heat treated on stainless steel. Used for HWCTR zero power tests. |
| 17 | U-2 w/o Zr | Thick wall | -- | Revere 3/11/58 | 16817 | Cut up | 4 | None | Mandrel broke during extrusion. Used in as-extruded condition for corrosion tests. |
| 18 | U-2 w/o Zr | Thick wall | -- | Revere 3/11/58 | 16818 | Stored SRL | 4 | -- | Thin cladding at rear end seal. Heat treated on both graphite and Mo pads. One end had white corrosion product. End seal section removed for U contamination analysis. Surface has several scratches. Used for HWCTR zero power tests. |
| 19 | U-2 w/o Zr | Thick wall | SPR-3 | Revere 3/11/58 | 16819 | Irradiated SRP | 4 | 6/30/58 | Heat treated on stainless steel. |
| 20 | U-2 w/o Zr | Thick wall | -- | Revere 3/11/58 | 16820 | Stored SRL | 4 | 4/11/58 | Heat treated on Mo. Has pad marks. Used in Canada as demonstration tube and for trial handling runs. Later used for HWCTR zero power tests. |
| 21 | U-2 w/o Zr | Thick wall | -- | Revere 3/11/58 | 16821 | Cut up | 4 | None | Mandrel broke during extrusion. Used for corrosion studies. End seals used for core end location studies. |
| 22 | U-2 w/o Zr | Thick wall | SPR-8 | ABC(6) 5/9/58 | 18393 | Irradiated SRP | 5 | 10/31/58 | Irradiated at SRP in low and high flux conditions. Failed during high flux portion of test. |
| 23 | U-2 w/o Zr | Thick wall | -- | ABC 5/9/58 | 18394 | Cut up | 5 | 11/3/58 | Used for corrosion studies, simulated spheroidizing heat treatment and growth index measurements. |
| 24 | U-2 w/o Zr | Thick wall | -- | ABC 5/23/58 | 18384 | Scrapped | 5 | None | Did not extrude because of press failure. Billet modified and used for temperature studies. |
| 25 | U-2 w/o Zr | Thick wall | -- | ABC 6/27/58 | 18385 | Cut up | 5 | 11/10/58 | Core had high carbon content. Used for corrosion studies and dissolution studies. |
| 26 | U-2 w/o Zr | Thick wall | -- | ABC 5/23/58 | 15386 | Stored SRL | 5 | 11/13/58 | Originally assigned to Chalk River. Later used for HWCTR zero power studies. Suitable for irradiation. Tube No. 72, unalloyed U, substituted for this tube for Chalk River (NRU) irradiation. |
| 27 | U-2 w/o Zr | Thick wall | -- | ABC 5/23/58 | 18387 | Cut up | 5 | None | Serious pick-up of Zr on die during extrusion. Used to check diffusion rates of copper for various heat treatments. |

(6) American Brass Company, Waterbury, Conn.

## Summary of Nuclear Metals Power Program Fuel Tubes (Continued)

| NM Tube Nbr. | Composition | Description | Irrad. Assy. Number | Extruder and Date | NM Extru. Number | Status and Location | Ref. Info. | Autoclave Test Completion | Comments |
|---|---|---|---|---|---|---|---|---|---|
| 28 | U-2 w/o Zr | Thick wall | SPR-7 | ABC 5/23/58 | 18388 | Irradiated SRP | 5 | 11/17/58 | Heat treated at 880°C for 7 hours. Re-heat treated at 680°C for 72 hours to spheroidize epsilon. |
| 29 | U- 2 w/o Zr | Thick wall | SPR-4 | ABC 6/27/58 | 18389 | Irradiated SRP | 5 | 11/20/58 | Failed during irradiation at SRP |
| 30 | U-2 w/o Zr | Thick wall | SPR-5 | ABC 6/27/58 | 13890 | Irradiated SRP | 5 | 11/24/58 | None. |
| 31 | U-2 w/o Zr | Thick wall | -- | ABC 6/27/58 | 18391 | Stored SRL | 5 | 11/28/58 | Originally assigned as spare for NRU irradiation. Later used for HWCTR zero power tests. Suitable for irradiation. |
| 32 | U-2 w/o Zr | Thick wall | -- | ABC 6/27/58 | 18392 | Stored SRL | 5 | 12/1/58 | Used for HWCTR zero power tests. |
| 33 | U-2 w/o Zr | Thick wall VBWR(7) | -- | ABC 10/10/58 | 19657 | Stored NM | 6 | -- | Pickled, X-rayed, autoradiographed and heat treated. Used for thermal cycling studies. |
| 34 | U-2 w/o Zr | Thick wall VBWR | SPR-9 | ABC 10/10/58 | 19658 | Irradiated SRP | 6 | 11/6/58 | Was not heat treated. Used by ABC as exhibition tube; sent to VBWR as demonstration tube; then sent to SRP for irradiation. Failed during irradiation at SRP. |
| 35 | U-2 w/o Zr | Thick wall VBWR | -- | ABC 10/10/58 | 19659 | Stored SRL | 6 | -- | Used for flow tests at SRL. |
| 36 | U-2 w/o Zr | Thick wall VBWR | -- | ABC 10/10/58 | 19660 | Stored NM | 6 | -- | Pickled, X-rayed, autoradiographed and heat treated. Questionable end seal bond. |
| 37 | U-2 w/o Zr | Thick wall VBWR | -- | ABC 12/12/58 | 19889 | Stored SRL | 6 | 1/4/59 | U enriched to 3.06% $^{235}U$. Required excessive extrusion pressure. Has questionable surface. |
| 38 | U-2 w/o Zr | Thick wall VBWR | -- | ABC 12/12/58 | 19890 | Cut up | 6 | None | U enriched to 3.06% $^{235}U$. Not heat treated. Destructively examined to obtain autoradiographic standards. Also used for growth index measurements to characterize tube No. 34. |
| 39 | U-2 w/o Zr | Thick wall VBWR | -- | ABC 12/12/58 | 19891 | Stored SRL | 6 | 1/26/59 | U enriched to 3.06% $^{235}U$. Possible candidate for limited irradiation. |
| 40 | U-2 w/o Zr | Thick wall VBWR | -- | ABC 12/12/58 | 19892 | Stored SRL | 6 | 2/9/59 | U enriched to 3.06% $^{235}U$. Suitable for irradiation. |
| 41 | U-2 w/o Zr | Thick wall VBWR | -- | ABC 12/12/58 | 19893 | Irradiated VBWR; stored SRL | 6 | 2/9/59 | U enriched to 3.06% $^{235}U$. Irradiated at VBWR to 1200 MWD/T. |
| 42 | U-2 w/o Zr | Thick wall VBWR | -- | ABC 12/12/58 | 19894 | Stored SRL | 6 | 2/9/59 | U enriched to 3.06% $^{235}U$. Formerly VBWR standby tube. Suitable for irradiation. |

(7) VBWR - Vallecitos Boiling Water Reactor fuel tubes.

## Summary of Nuclear Metals Power Program Fuel Tubes (Continued)

| NM Tube Nbr. | Composition | Description | Irrad. Assy. Number | Extruder and Date | NM Extr. Number | Status and Location | Ref. Info. | Autoclave Test Completion | Comments |
|---|---|---|---|---|---|---|---|---|---|
| 43 | 90 Cu-10 Ni | Experimental | -- | ABC 12/12/58 | -- | Cut up | NMI-4383, 4384 | None | Experimental tube to study cost reduction items. Samples sent to SRL for burst tests. |
| 44 | Zr-9.3 w/o U | Prototype HWCTR driver | -- | ABC 3/21/59 | 20744 | Stored SRL | 7 | None | Less than best extrusion flow shape design. Was cold drawn and machined. Used for flow tests at SRL. |
| 45 | Zr-9.3 w/o U | Prot. HWCTR driver | -- | ABC 3/21/59 | 20745 | Cut up | 7 | None | Used for U distribution measurements in as-extruded condition. |
| 46 | Zr-9.3 w/o U | Prot. HWCTR driver | -- | ABC 3/21/59 | 20746 | Cut up | 7 | None | Best extrusion flow shape design. Used for destructive evaluation. |
| 47 | Zr-9.3 w/o U | Prot. HWCTR driver | -- | ABC 3/21/59 | 20747 | Cut up | 7 | None | Less than best extrusion flow shape design. Section used for straightening experiments. |
| 48 | Zr-9.3 w/o U | Prot. HWCTR driver | -- | ABC 3/21/59 | 20748 | Cut up | 7 | None | Cold drawn. U distribution determined in cold drawn condition. |
| 49 | Zr-9.3 w/o | Prot. HWCTR driver | -- | ABC 3/21/59 | 20749 | Cut up | 7 | 6/1/59 | Best flow shape. Used for destructive evaluation. |
| 50 | Unalloyed U | Thick wall | -- | ABC 5/8/59 | 20918 | Cut up | 8 | None | High carbon, 30-mil clad, beta treated. U broke thru during extrusion at front and rear ID. Core end tapers cut off for evaluation. |
| 51 | Unalloyed U | Thick wall | -- | ABC 5/8/59 | 20919 | Stored SRL | 8 | None | High carbon, 30-mil clad. Fluctuations in I.D. clad thickness along core (min. 9.4 mils after pickling). Beta heat treated and used in gamma heat treating test. Has shallow fiducial marks on surface. Was not machined or etched. Used for HWCTR zero power tests. |
| 52 | Unalloyed U | Thick wall | -- | ABC 5/8/59 | 20920 | Cut up | 8 | None | High carbon, 20-mil inside clad, 40-mil outside clad. Beta treated. U broke through during extrusion at front and rear I.D. End tapers cut off for evaluation. |
| 53 | Unalloyed U | Thick wall | SPR-11 | ABC 5/8/59 | 20921 | Irradiated SRP | 8 | June,'59 | Low carbon, 30-mil clad. Beta treated. Minimum cladding 10 mils. |
| 54 | Unalloyed U | Thick wall | -- | ABC 5/8/59 | 20922 | Stored NM | 8 | Failed Oct.,'59 | Failed during autoclave test. |
| 55A | Unalloyed U | Thick wall | -- | ABC 5/8/59 | 20923 | Stored NM | 8 | None | High carbon, 20-mil clad. Fluctuations in I.D. clad. Thickness along core. As-extruded with copper jacket intact. Tandem extruded with tube 55B. |
| 55B | Unalloyed U | Thick wall | -- | ABC 5/8/59 | 20923 | Cut up | 8 | None | Low carbon, 30-mil clad. Fluctuations in I.D. clad. thickness along core. |
| 56 | Zr-9.3 w/o U | Prot. HWCTR driver | -- | ABC 7/11/59 | 21287 | Cut up | 9 | None | Used to evaluate core length. |
| 57 | Zr-9.3 w/o U | Prot. HWCTR driver | -- | ABC 7/11/59 | 21288 | Cut up | 9 | None | Used to evaluate core length. |

## Summary of Nuclear Metals Power Program Fuel Tubes (Continued)

| NM Tube Nbr. | Composition | Description | Irrad. Assy. Number | Extruder and Date | NM Extru. Number | Status and Location | Ref. Info. | Autoclave Test Completion | Comments |
|---|---|---|---|---|---|---|---|---|---|
| 58 | Zr-9.3 w/o U | Prot. HWCTR driver | -- | ABC 7/24/59 | 21336 | Stored SRL | 9 | Aug. '59 | U enriched to 93% $^{235}U$. Grooves in outside cladding caused by copper pickup on extrusion die. Was used as NTG(8) standard at SRP. |
| 59 | Zr-9.3 w/o U | Prot. HWCTR driver | SPRD-12 | ABC 7/24/59 | 21337 | Irradiated SRP | 9 | Aug. '59 | U enriched to 93% $^{235}U$. |
| 60 | Zr-9.3 w/o U | Prot. HWCTR driver | SPRD-13 | ABC 7/24/59 | 21338 | Irradiated SRP | 9 | Aug. '59 | U enriched to 93% $^{235}U$. Tube had grooves similar but not as deep as grooves on tube No. 58. U was above nominal at 9.8%. |
| 61A | U-1 w/o Si | Thick wall VBWR | -- | ABC 9/25/59 | 21721A | Cut up | 10 | None | A short tandem tube extruded with tube No. 61B to study end shape, clad thickness, heat treatment and bond quality. |
| 61B | U-1.5 w/o Mo | Thick wall VBWR | -- | ABC 9/25/59 | 21721B | Cut up | 10 | None | Used to study effect of heat treatment on bond strength. |
| 62 | U-1 w/o Si | Thick wall | -- | ABC 9/25/59 | 21722 | Stored SRL | 10 | None | A full length tube rejected for surface dimples on O.D. and I.D. caused by poor quality copper sleeves. Thread-machined. Used for HWCTR zero power tests. |
| 63 | U-1.5 w/o Mo | Thick wall | -- | ABC 9/25/59 | 21723 | Stored SRL | 10 | None | Bond strength uncertain. Clad thinned to 8.3 mils at rear I.D. Much ripple on O.D. Not heat treated, etched, or machined. Used for HWCTR zero power tests. |
| 64 | Unalloyed U | Thick wall | -- | ABC 11/6/59 | 22076 | Cut up | 11 | None | Short experimental tube to investigate effect of billet end shapes on thinning. Power tube end shapes used. |
| 65 | Unalloyed U | Thick wall | -- | ABC 11/6/59 | 22077 | Cut up | 11 | None | Short experimental tube to investigate effect of billet end shapes on thinning. Modified power tube end shapes used. |
| 66 | Unalloyed U | Thick wall | -- | ABC 11/6/59 | 22078 | Cut up | 11 | None | Short experimental tube to investigate effect of billet end shapes on thinning. Single-notch end shape used. |
| 67 | Unalloyed U | Thick wall | -- | ABC 11/6/59 | 22079 | Cut up | 11 | None | Short experimental tube to investigate effect of billet end shapes on thinning. Saw-tooth end shape used. |
| 68 | Unalloyed U | Thick wall VBWR | -- | ABC 12/11/59 | 23165 | Stored SRL | 11 | Dec. '59 | U enriched to 3.10% $^{235}U$. Single-tooth end shape used in billet design. Suitable for irradiation. |
| 69 | Unalloyed U | Thick wall VBWR | -- | ABC 12/11/59 | 23166 | Stored SRL | 11 | Dec. '59 | U enriched to 3.10% $^{235}U$. Single-tooth end shape used in billet design. Suitable for irradiation. |
| 70 | U-1 w/o Si | Thick wall VBWR | -- | ABC 2/19/60 | 27323 | Cut up | 12 | None | Prototype tube for VBWR. Unalloyed Zr end shapes used with clad thickness 20 mils. Destructive evaluation made. |
| 71 | U-1.5 w/o Mo | Thick wall VBWR | -- | ABC 2/19/60 | 27324 | Cut up | 12 | None | Prototype tube for VBWR. Saw-tooth end shape used in billet design. Thin clad at rear of 14 mils. Destructively evaluated. |

(8) NTG - Nuclear Test Gage at Savannah River Plant.

## Summary of Nuclear Metals Power Program Fuel Tubes (Continued)

| NM Tube Nbr. | Composition | Description | Irrad. Assy. Number | Extruder and Date | NM Extru. Number | Status and Location | Ref. Info. | Autoclave Test Completion | Comments |
|---|---|---|---|---|---|---|---|---|---|
| 72 | Unalloyed U | Thick wall | -- | ABC 2/19/60 | 27325 | Irradiated NRU | 13 | March '60 | Beta treated and air cooled at SRL. Irradiated in E-20 loop in NRU. Thin 10-mil cladding at front O.D. |
| 73 | Unalloyed U | Thick wall | -- | ABC 2/10/60 | 27326 | Cut up | 13 | None | Beta treated and air cooled at SRL. Inclusion in O.D. cladding with pit 8 mils deep. |
| 74 | Unalloyed U | Thin wall Outer | -- | NM 4/8/60 | 27944 | Stored SRL | 14 | May '60 | Not heat treated. Used for flow tests at SRL. |
| 74A | Unalloyed U | Thin wall Outer | -- | NM 4/8/60 | 27746 | Cut up | 14 | None | Modified angular end shape used in billet. Some breakthrough of core occurred during extrusion. |
| 74B | Unalloyed U | Thin wall Outer | -- | NM 4/8/60 | 27747 | Cut up | 14 | None | Used Hanford-style spherical end shape in billet. |
| 75 | Unalloyed U | Thin wall Outer | TWT-2(9) | NM 4/22/60 | 27943 | Irradiated SRP | 14 | May '60 | Beta heat treated and air cooled at Atlas Steels, Ltd., Welland, Ontario. |
| 76 | Unalloyed U | Thin wall Outer--VBWR | -- | NM 4/22/60 | 27942 | Cut up | 14 | None | Destructively evaluated. |
| 77 | U-1 w/o Si | Thin wall Outer--VBWR | -- | ABC 4/23/60 | 28551 | Cut up | 15 | None | Prototype for VBWR test. Destructively evaluated for end-seal clad thinning. |
| 78 | U-1.5 w/o Mo | Thin wall Outer--VBWR | -- | ABC 4/23/60 | 28552 | Cut up | 15 | None | Prototype for VBWR test. Destructively evaluated for end-seal clad thinning. Also used to evaluate braze seals. |
| 79 | U-1 w/o Si | Thin wall Outer--VBWR | -- | ABC 4/23/60 | 28553 | Stored SRL | 15 | May '60 | U enriched to 3% $^{235}U$. Suitable for irradiation. |
| 80 | U-1.5 w/o Mo | Thin wall Outer--VBWR | -- | ABC 6/16/60 | 28874 | Cut up | 15 | None | VBWR prototype. Destructively evaluated for end-seal clad thinning; no thinning found. Also used to evaluate braze seals. |
| 81 | U-1.5 w/o Mo | Thin wall Outer--VBWR | -- | ABC 6/16/60 | 28875 | Cut up | 15 | None | VBWR prototype. Destructively evaluated with 15-mil thinning found at rear. |
| 82 | U-1.5 w/o Mo | Thin wall Outer--VBWR | 3EMT-2 (10) | ABC 6/16/60 | 29115 | Irradiated HWCTR | 15 | May '60 | U enriched to 3% $^{235}U$. |
| 83 | U-1.5 w/o Mo | Thin wall Outer--VBWR | -- | ABC 7/8/60 | 29116 | Stored SRL | 15 | Sept. '62 | U enriched to 3% $^{235}U$. Suitable for irradiation. |
| 84 | Unalloyed U | Thin wall Outer | -- | NM June'60 | 28137 | Cut up | 16 | None | Billet design used 10° core bevels plus other preshaping with larger angles. |
| 85 | Unalloyed U | Thin wall Outer | -- | NM May'60 | 28133 | Cut up | 16 | None | Billet design used stepped end shape. Portions of tube used for transient melting studies. |
| 86 | Unalloyed U | Thin wall Outer | -- | NM May'60 | 28136 | Cut up | 16 | None | Similar to tube No. 84. |

(9) SRP number, TWT - thin-walled tube.
(10) HWCTR number, EMT - enriched metal tube.

## Summary of Nuclear Metals Power Program Fuel Tubes (Continued)

| NM Tube Nbr. | Composition | Description | Irrad. Assy. Number | Extruder and Date | NM Extru. Number | Status and Location | Ref. Info. | Autoclave Test Completion | Comments |
|---|---|---|---|---|---|---|---|---|---|
| 87 | Unalloyed U | Thin wall Outer | -- | NM May '60 | 28134 | Cut up | 16 | None | Billet design used uncompensated radius. |
| 88 | Unalloyed U | Thin wall Outer | -- | NM July'60 | 28138 | Cut up | 16 | None | Billet design used tapered inner sleeve at rear with front the same as tube No. 84. |
| 89 | Unalloyed U | Thin wall Outer | -- | NM July'60 | 28140 | Cut up | 16 | None | Billet design used short 10° core bevels. |
| 90 | Unalloyed U | Thin wall Outer | -- | NM May '60 | 28127 | Cut up | 16 | None | Billet design used flat 0° compensation. |
| 91 | Unalloyed U | Thin wall Outer | -- | NM May '60 | 28130 | Cut up | 16 | None | Billet design used flat + 26° compensation. |
| 92 | Unalloyed U | Thin wall Outer | -- | NM May '60 | 28132 | Cut up | 16 | None | Billet design used flat 45° compensation. |
| 93 | Unalloyed U | Thin wall Outer | -- | NM May '60 | 28129 | Cut up | 16 | None | Billet design used flat -15° compensation. |
| 94 | Unalloyed U | Thin wall Outer | -- | NM May '60 | 28126 | Cut up | 16 | None | Billet design used flat -27° compensation. |
| 95 | Unalloyed U | Thin wall Outer | -- | NM 6/18/60 | 28965 | Stored SRL | 16 | Nov.'60 | Oil-quenched at SRL; air cooled, beta treated at Atlas on 10/4/60. Flow tested at SRL. |
| 96 | Unalloyed U | Thin wall Outer | -- | NM 6/18/60 | 28966 | Stored NM | 16 | None | Billet design same as tube No. 84. Beta treated and air cooled at SRL. Damaged during extrusion press failure. Stored in as-pickled condition. |
| 97 | Unalloyed U | Thin wall Outer | -- | NM 6/18/60 | 28967 | Stored SRL | 16 | Nov.'60 | Oil-quenched at SRL; air cooled, beta treated at Atlas on 10/4/60. Flow tested at SRL. |
| 98 | Unalloyed U | Thin wall Outer- VBWR | -- | NM 6/18/60 | 28968 | Cut up | 16 | None | VBWR prototype. Billet design used long 10° core bevels. |
| 99 | Unalloyed U | Thin wall Outer | -- | NM July'60 | 28142 | Cut up | 16 | None | Billet design used long 10° core bevels. |
| 100 | Unalloyed U | Thin wall Inner | -- | NM June'60 | 29205 | Cut up | 17 | None | Destructively evaluated for end-seal clad-thinning. |
| 101 | Unalloyed U | Thin wall Inner | -- | NM June'60 | 29206 | Cut up | 17 | None | Destructively evaluted for end-seal clad-thinning. Billet design used 10° core bevels. Sections used for microstructure analysis at SRL. |
| 102 | Unalloyed U | Thin wall Inner | -- | NM June '60 | 29207 | Cut up | 17 | None | Destructively evaluated for end-seal clad-thinning. |
| 103 | Unalloyed U | Thin wall Inner | TWIT-3 (11) | NM 8/5/60 | 29309 | Irradiated SRP | 17 | Oct.'60 | Air-cooled at Atlas on 10/4/60. |
| 104 | Unalloyed U | Thin wall Inner | TWIT-3 | NM 8/5/60 | 29310 | Irradiated SRP | 17 | Oct.'60 | Air-cooled at Atlas on 10/4/60. |

(11) SRP number, TWIT - thin-walled inner tube.

## Summary of Nuclear Metals Power Program Fuel Tubes (Continued)

| NM Tube Nbr. | Composition | Description | Irrad. Assy. Number | Extruder and Date | NM Extru. Number | Status and Location | Ref. Info. | Autoclave Test Completion | Comments |
|---|---|---|---|---|---|---|---|---|---|
| 105 | Unalloyed U | Thin wall Inner | -- | NM 8/5/60 | 29311 | Stored SRL | 17 | None | Not heat treated. Used for flow tests at SRL. |
| 106 | Unalloyed U | Thin wall Outer- VBWR | -- | NM 8/30/60 | 29589 | Cut up | 16 | None | VBWR prototype. Thinning at front ID. |
| 107 | Unalloyed U | Thin wall Outer | -- | NM 9/2/60 | 29593 | Cut up | 18 | None | Destructive evaluation showed good centering of front taper. Cladding uniform with 20 mils minimum. |
| 108 | Unalloyed U | Thin wall Outer | TWT-3 | NM 9/23/60 | 29778 | Irradiated SRP | 18 | Nov.'60 | Air cooled at Atlas on 10/4/60. |
| 109 | Unalloyed U | Thin wall Outer | -- | NM 9/23/60 | 29779 | Stored at NM | 18 | Nov.'60 | Air cooled at Atlas on 10/4/60. Very irregular cladding as indicated by eddy current examination. Stored in autoclaved condition. |
| 110 | Unalloyed U | Thin wall Outer | -- | NM 9/23/60 | 29780 | Stored NM | 18 | Nov.'60 | Air cooled at Atlas on 10/4/60. |
| 111 | Unalloyed U | Thin wall Outer | -- | NM 9/23/60 | 29781 | Stored SRL | 18 | Nov.'60 | Breakthrough during extrusion. Air cooled at Atlas on 10/4/60. Used for flow tests at SRL. |
| 112 | Unalloyed U | Thin wall Outer | -- | NM 9/23/60 | 29782 | Stored NM | 18 | Nov.'60 | Air cooled at Atlas on 10/4/60. Double-autoclaved. Used for autoclave straightening tests. |
| 113 | Unalloyed U | Thin wall Outer- VBWR | -- | NM 9/29/60 | 29861 | Cut up | 16 | None | VBWR prototype. |
| 114 | Unalloyed U | Thin wall Outer- VBWR | -- | NM 10/19/60 | 30103 | Stored SRL | 19 | Nov.'60 | U enriched to 3% $^{235}U$. Some shallow depressions less than 3 mils. Suitable for irradiation. |
| 115 | Unalloyed U | Thin wall Outer- VBWR | -- | NM 10/19/60 | 30104 | Stored SRL | 19 | Nov.'60 | U enriched to 3% $^{235}U$. Some shallow depressions. Suitable for irradiation. |
| 116 | Unalloyed U | Thin wall Inner | -- | NM 12/2/60 | 30795 | Stored NM | 20 | None | Inner tube demonstration set. Surface scratches on ID. |
| 117 | Unalloyed U | Thin wall Inner | TWIT-2 | NM 12/2/60 | 30796 | Irradiated SRP | 20 | Jan.'61 | Inner tube demonstration set. |
| 118 | Unalloyed U | Thin wall Inner | -- | NM 12/2/60 | 30797 | Stored NM | 20 | None | Inner tube demonstration set. Surface scratches on ID. |
| 119 | Unalloyed U | Thin wall Inner | TWIT-2 | NM 12/2/60 | 30798 | Irradiated SRP | 20 | Jan.'61 | Inner tube demonstration set. |
| 120 | Unalloyed U | Thin wall Inner | -- | NM 12/2/60 | 30799 | Stored SRL | 20 | None | Inner tube demonstration set. Used for flow tests at SRL. |
| 121 | Unalloyed U | Thin wall Inner | -- | NM 12/2/60 | 30800 | Stored SRL | 20 | Dec.'60 | Not heat treated. Used for flow tests at SRL. |

## Summary of Nuclear Metals Power Program Fuel Tubes (Continued)

| NM Tube Nbr. | Composition | Description | Irrad. Assy. Number | Extruder and Date | NM Extru. Number | Status and Location | Ref. Info. | Autoclave Test Completion | Comments |
|---|---|---|---|---|---|---|---|---|---|
| 122 | Unalloyed U | Thin wall Outer | -- | NM 2/24/61 | 31229 | Cut up | 21 | None | Experimental tube to improve core-clad interface. Core prepared by upset-extrusion of triple beta treated casting. Marked improvement noted. |
| 123 | Unalloyed U | Thin wall Outer | -- | NM 2/24/61 | 31230 | Cut up | 21 | None | Experimental tube to improve core-clad interface using a chilled casting with core processing similar to tube No. 122. Severe shift caused by ram-mandrel misalignment. |
| 124 | Unalloyed U | Thin wall Outer | -- | NM 5/4/61 | 31873 | Cut up | 21 | None | Evaluation of solid Zr billet nose. |
| 125 | Unalloyed U | Thin wall Outer | -- | NM 5/18/61 | 32001 | Stored NM | 22 | July '61 | HWCTR outer tube prototype. |
| 126 | Unalloyed U | Thin wall Outer | -- | NM 5/18/61 | 32002 | Stored NM | 22 | July '61 | HWCTR outer tube prototype. |
| 127 | Unalloyed U | Thin wall Outer | -- | NM 5/18/61 | 32003 | Stored NM | 22 | July '61 | HWCTR outer tube prototype. |
| 128 | Unalloyed U | Thin wall Inner | -- | NM 5/26/61 | 32039 | Stored NM | 23 | Aug. '61 | Type D restraint tube with 60 mil cladding both OD and ID. 5-8 mil striation in cladding. |
| 129 | Unalloyed U | Thin wall Inner | -- | NM 5/26/61 | 32040 | Stored SRL | 23 | Aug. '61 | Type E restraint tube with 40 mil OD clad and 25 mil ID clad. Suitable for irradiation. |
| 130 | Unalloyed U | Thin wall Outer | -- | NM 6/15/61 | 32345 | Stored SRL | 24 | Aug. '61 | Type B restraint tube with 25 mil OD clad and 40 mil ID clad. Suitable for irradiation. |
| 131 | Unalloyed U | Thin wall Outer | -- | NM 6/15/61 | 32346 | Stored SRL | 24 | Aug. '61 | Type C restraint tube with 40 mil OD clad and 25 mil ID clad. Suitable for irradiation. |
| 132 | Unalloyed U | Thin wall Outer | -- | ABC 8/25/61 | 32995 | Stored NM | 24 | Oct. '61 | Restraint tube with 60 mil OD and ID cladding. Slight white oxide over 2 ft. span caused by autoclave malfunction. |
| 133 | Unalloyed U | Thin wall Outer | RMT-1-2 (12) | ABC 8/25/61 | 32996 | Irradiated HWCTR | 24 | Jan. '62 | Type A restraint tube with 60 mils OD and ID cladding. |
| 134 | U-1 w/o Si | Thin wall Outer | -- | ABC 8/25/61 | 32997 | Scrapped | 25 | None | Experimental alloy tube. Stalled in extrusion press. |
| 135 | U-0.3 w/o Al -0.5 w/o Si | Thin wall Outer | -- | ABC 8/25/61 | 32998 | Stored SRL | 25 | Jan. '62 | Experimental ternary alloy tube. Suitable for irradiation. |
| 136 | Unalloyed U | Thin wall Inner | -- | NM 9/9/61 | 33158 | Stored SRL | 23 | Jan. '62 | Type D restraint tube with 60 mils OD and ID cladding. Replacement for tube No. 128. Suitable for irradiation. |

(12) HWCTR number, RMT - Restraint metal tube.

## Summary of Nuclear Metals Power Program Fuel Tubes (Continued)

| NM Tube Nbr. | Composition | Description | Irrad. Assy. Number | Extruder and Date | NM Extru. Number | Status and Location | Ref. Info. | Autoclave Test Completion | Comments |
|---|---|---|---|---|---|---|---|---|---|
| 137 | Unalloyed U | Thin wall Inner | -- | NM 2/14/62 | -- | Cut up | 26 | None | Prototype for HWCTR enriched tubes for scouting billet design parameters and to evaluate non bond standards. |
| 138 | Unalloyed U | Thin wall Outer | -- | NM 3/8/62 | 35820 | Cut up | 27 | None | Demonstration of Process B core preparation. |
| 139 | Unalloyed U | Thin wall Outer | -- | NM 3/8/62 | 35821 | Cut up | 27 | None | Demonstration of Process B core preparation. |
| 140 | Unalloyed U | Thin wall Outer | -- | NM 3/8/62 | 35819 | Cut up | 27 | None | Demonstration of Process B core preparation. |
| 141 | U-1 w/o Si | Thin wall Outer | -- | ABC 4/14/62 | 35897 | Stored SRL | 25 | June '62 | Experimental alloy tube. Suitable for irradiation. |
| 142 | U-1.5 w/o Mo | Thin wall Outer | -- | ABC 4/14/62 | -- | Stored NM | 25 | None | Experimental alloy tube. Stored in as-extruded condition. |
| 143 | Unalloyed U | Thin wall Inner | -- | NM 4/27/62 | 35929 | Stored SRL | 26 | June '62 | U enriched to 2.1% $^{235}U$. Oil quenched at SRL. Suitable for irradiation. ("No.1" marked on tube.) |
| 144 | Unalloyed U | Thin wall Inner | -- | NM 4/27/62 | 35930 | Stored SRL | 26 | June '62 | U enriched to 2.1% $^{235}U$. Air cool heat treatment at Watertown Arsenal. Suitable for irradiation. ("No. 2" marked on tube.) |
| 145 | Unalloyed U | Thin wall Inner | -- | NM 4/27/62 | 35931 | Stored SRL | 26 | Nov. '62 | U enriched to 2.1% $^{235}U$. Oil quenched at SRL. Suitable for irradiation. |
| 146 | Unalloyed U | Thin wall Inner | -- | NM 4/27/62 | 35932 | Stored SRL | 26 | Nov. '62 | U enriched to 2.1% $^{235}U$. Oil quenched at SRL. Irregular cladding thickness. Suitable for limited irradiation. |
| 147 | Unalloyed U | Thin wall Inner | -- | NM 4/27/62 | 35933 | Stored SRL | 26 | June '62 | U enriched to 2.1% $^{235}U$. Oil quenched at SRL. Suitable for irradiation. ("5" marked on tube.) |
| 148 | Unalloyed U | Thin wall Outer | ETWO-2 (13) | NM 6/29/62 | 36308 | Irradiated HWCTR | 28 | Jan. '63 | U enriched to 2.1% $^{235}U$. Oil quenched at SRL. |
| 149 | Unalloyed U | Thin wall Outer | ETWO-3 | NM 6/29/62 | 36309 | Irradiated HWCTR | 28 | Jan. '63 | U enriched to 2.1% $^{235}U$. Oil quenched at SRL. |
| 150 | Unalloyed U | Short HWCTR | -- | NM 11/5/62 | 36692 | Cut up | 29 | None | Braze development. |
| 151 | Unalloyed U | Short HWCTR | -- | NM 11/5/62 | 36693 | Stored SRL | 29 | March '63 | Tube cut into 11½" sections with end caps brazed. Six sections sent to SRL as irradiation candidates. |
| 152 | U-350 Fe-900 Al (14) | Short HWCTR | -- | NM 12/26/62 | 36823 | Cut up | 29 | None | Braze development. |

(13) HWCTR number, ETWO - Enriched thin wall outer tube.
(14) Quantities are given in ppm.

## Summary of Nuclear Metals Power Program Fuel Tubes (Continued)

| NM Tube Nbr. | Composition | Description | Irrad. Assy. Number | Extruder and Date | NM Extru. Number | Status and Location | Ref. Info. | Autoclave Test Completion | Comments |
|---|---|---|---|---|---|---|---|---|---|
| 153 | U-350 Fe-900 Al | Short HWCTR | SMT-1-2 (15) | NM 12/26/62 | 36824 | Irradiated HWCTR | 29 | March '63 | Tube cut into 11½" sections with end caps brazed. Section Nos. 153-2, 3, 4, 6 and 7 irradiated. |
| 154 | U-350 Fe-900 Al (Gamma) | Short HWCTR | SMT-1-2 | NM 12/26/62 | 36825 | Irradiated HWCTR | 29 | March '63 | Tube cut into 11½" sections with end caps brazed. Section Nos. 154-2, 4, 5, 6 and 7 irradiated. |
| 155 | U-350 Fe-900 Al-500 Si-1000 Mo | Short HWCTR | -- | NM 12/26/62 | 36826 | Stored NM | 29 | None | Short tube intended to provide stock for physical metallurgical studies. |
| 156 | Zr-2, 6.5 w/o U | Outer HWCTR Driver | -- | NM 11/30/62 | 36957 | Scrapped | 30 | None | Did not extrude; stalled in press. Billet was reworked and used for a second extrusion. |
| 157 | U-350 Fe-900 Al-300 Si | Short HWCTR | -- | NM 3/11/63 | 37108 | Stored NM | 29 | None | Core had crack-like defects. Used for brazing development and standard for ultrasonic test. |
| 158 | U-350 Fe-900 Al-300 Si | Short HWCTR | SMT-1-3 | NM 3/11/63 | 37109 | Irradiated HWCTR | 29 | March '63 | Tube cut into 11½" sections with end caps brazed. Section Nos. 158-3, 4, 5, 6 and 7 irradiated. |
| 159 | Zr-2, 6.5 w/o U | Outer HWCTR Driver | -- | NM 5/22/63 | - | Cut up | 30 | None | Destructively evaluated. |
| 160 | Zr-2, 6.5 w/o U | Inner HWCTR Driver | -- | NM 6/14/63 | - | Cut up | 31 | None | Used for feasibility tests of electron beam welding of 0.060" thick x 0.300" high ribs onto shallow integral ribs of tube by Dresser Products, Inc. |
| 161 | Zr-2, 6.5 w/o U | Inner HWCTR Driver | -- | NM 8/9/63 | - | Cut up | 31 | None | Destructively evaluated. |
| 162 | Zr-2, 6.5 w/o U | Inner HWCTR Driver | -- | NM 8/9/63 | - | Stored NM | 31 | None | Shallow integral ribs did not bond - used rib stock inserted in billet as Zircaloy strips (same as for tubes 160 & 161). |
| 163 | Zr-2, 6.5 w/o U | Outer HWCTR Driver | -- | NM 8/13/63 | - | Cut up | 30 | None | Destructively evaluated. |
| 164 | Zr-2, 6.5 w/o U | Outer HWCTR Driver | -- | NM 8/13/63 | - | Stored SRL | 30 | None | Used for flow test at SRL. |
| 165 | Zr-2, 6.5 w/o U | Inner HWCTR Driver | -- | NM 9/25/63 | - | Stored NM | 31 | None | Fabricated with rib stock machined as part of outer Zircaloy sleeve of billet with satisfactory results. |
| 166 | Zr-2, 6.5 w/o U | Inner HWCTR Driver | -- | NM 9/25/63 | - | Stored NM | 31 | None | Same as tube 165. |

(15) HWCTR number, SMT - Segmented metal tube.

## Summary of Nuclear Metals Power Program Fuel Tubes (Continued)

| NM Tube Nbr. | Composition | Description | Irrad. Assy. Number | Extruder and Date | NM Extru. Number | Status and Location | Ref. Info. | Autoclave Test Completion | Comments |
|---|---|---|---|---|---|---|---|---|---|
| 167 | Zr-2, 11.1 w/o U | Single HWCTR Driver | -- | NM 11/6/63 | -- | Cut up | 32 | None | Destructively evaluated. |
| 168 | Zr-2, 11.1 w/o U | Single HWCTR Driver | -- | NM 11/27/63 | -- | Cut up | 32 | None | Destructively evaluated. |
| 169 | Zr-2, 11.1 w/o U | Single HWCTR Driver | -- | NM 1/7/64 | -- | Cut up | 32 | None | Destructively evaluated. |
| 1-1 | Th-1.6 w/o U | Th metal fuel tube | -- | SRL 4/2/64 | -- | Cut up | 33 | None | Destructively evaluated. |
| 1-2 | Th-1.6 w/o U | Th metal fuel tube | -- | SRL 4/2/64 | -- | Cut up | 33 | None | Destructively evaluated. |
| 1-3 | Th-1.6 w/o U | Th metal fuel tube | TMT-1-1 (16) | SRL 4/2/64 | -- | Stored SRL | 33 | None | Used for long term flow tests at SRL. |
| 1-4 | Th-1.6 w/o U | Th metal fuel tube | -- | SRL 7/9/64 | -- | Stored SRL | 33 | None | This tube was not evaluated. |
| 2-1 | Th-1.5 w/o U | Th metal fuel tube | TMT-1-2 | SRL 7/9/64 | -- | Irradiated HWCTR | 33 | July '64 | U enriched to 93% $^{235}U$ |
| 2-2 | Th-1.5 w/o U | Th metal fuel tube | -- | SRL 7/9/64 | -- | Stored SRL | 33 | None | U enriched to 93% $^{235}U$. Not suitable for irradiation because of ring markings on the inner surface at each end of the tube. |
| 2-3 | Th-1.5 w/o U | Th metal fuel tube | TMT-1-3 | SRL 7/9/64 | -- | Irradiated HWCTR | 33 | July '64 | U enriched to 93% $^{235}U$. |
| TWOTs | Unalloyed U | Thin wall outer tubes | TWNT (17) | NM 1962 | -- | 8 tubes irradiated HWCTR. Remaining 7 stored SRL | 34 | All tubes autoclaved | 15 of these tubes were fabricated as part of a nested pairs of tubes for irradiation in HWCTR. 7 were irradiated as nested pairs of outers and inners with spiral ribbon spacers. Two of the assemblies failed. One was irradiated individually as HWCTR Assy. No. TWO-1-2. |
| TWITs | Unalloyed U | Thin wall inner tubes | TWNT | NM 1962 | -- | 7 tubes irradiated HWCTR. Remaining 8 stored SRL. | 35 | All tubes autoclaved | Same as for TWOTs, 15 tubes fabricated. |

(16) HWCTR number, TMT - Thorium metal tube.
(17) HWCTR number, TWNT - Thin wall nested tubes.

## Summary of Nuclear Metals Power Program Fuel Tubes (Continued)

| NM Tube Nbr. | Composition | Description | Irrad. Assy. Number | Extruder and Date | NM Extru. Number | Status and Location | Ref. Info. | Autoclave Test Completion | Comments |
|---|---|---|---|---|---|---|---|---|---|
| M-1 & M-2 Drivers | Zr-9.3 w/o U | HWCTR Driver Tubes | M-1 & M-2 | ABC 1960 | -- | 48 tubes were irradiated HWCTR, 24 as M-1 set, 24 as M-2 set. Remaining tubes are stored SRL | 36 | 13 of the 56 tubes tested | U enriched to 93% $^{235}U$. 56 tubes were fabricated; 53 suitable for irradiation, and 3 rejected for minor defects. |
| M-3 Drivers | Zr-2, 11.1 w/o U | HWCTR Single Tube Driver | M-3 | NM 1964 | -- | Stored SRL | 37 | 8 of the 28 tubes tested | U enriched to 93% $^{235}U$. 28 tubes were fabricated; 24 suitable for irradiation. HWCTR operation terminated prior to use of this driver set. |

## APPENDIX A

1. NM Tube Nos. 1-3

Ref: Progress Reports NMI-4355, 4356.

These three tubes were the first group of full-scale extrusions of Zircaloy-2 clad U-2 w/o Zr fuel. Extrusion was performed at 663°C with tube No. 1 not being extruded. The remaining two tubes, Nos. 2 and 3, were destructively examined following their extrusion. No detailed data were published.

2. NM Tube Nos. 4-9

Ref: (1) Progress Reports NMI-4350, 4356, 4357.

(2) Letter, 3/25/58, J. L. Klein, N.M., to P. H. Permar, SRL, "SRL and NRU Flow Test Tubes (5 and 8)".

Of this group of 6 tubes, 2 were shipped to SRL for flow tests. The remaining 4 tubes were cut up for destructive evaluation and other uses. Data for tubes 5 and 8 are presented below.

A. Description

Thick wall tubes, 2.060" OD X 0.297" wall (nominal).

No. 5 - SRL flow test tube (Drawing ST-MDX3-1552)
No. 8 - NRU " " " (Drawing ST-MDX4-1598)

B. Composition

Core: U-2 w/o Zr alloy.

Cladding: Zircaloy-2 (15 mils nominal thickness).

End seals: Integral-type Zircaloy-2.

C. Dimensions

Taken before final bright etching. Approximately 2 mils removed from each surface during bright etching; therefore, I.D. should be increased by ~0.004" and O.D. decreased by ~0.004".

| | Tube 5 (inches) | Tube 8 (inches) |
|---|---|---|
| Over uniform core OD | 2.060 | 2.056 |
| ID | 1.447 | 1.447 |
| Over end seals, OD | 2.079 | 2.079 |
| ID | 1.464 | 1.467 |
| Overall length | 132 | 132 |
| Core, tip-to-tip | 115-7/8 | 115-7/8 |

D. Extrusion Conditions

(Done at Revere Copper & Brass Co., Detroit, Michigan)

| | NM Extrusion Number |
|---|---|
| Tube No. 5 | 15992 |
| Tube No. 8 | 15995 |

Copper-clad billet.
Copper cutoff.
Tools heated to 540°C.
Extrusion at 650°C in a 2400-ton press. (For tube No. 8, force, running - 1625 tons with 1875 tons maximum.)

E. Heat Treatment - none.

F. Autoclave Test - none.

G. Remarks

Both tubes were used for flow tests and HWCTR zero power tests at SRL.

H. Current Conditions

Tubes 5 and 8 are stored at SRL.

These tubes are not suitable for irradiation.

3. NM Tube Nos. 10-16

Ref: (1) Progress Reports NMI-4357, 4358, 4359, 4361, 4362, 4366.

(2) NMI-4360, 4/19/58, J. L. Klein, "Evaluation of Three Zircaloy-clad U-2 w/o Zr Fuel Tubes (11, 14 & 15)".

Four of the 7 tubes were sent to SRL, 2 (11 and 15) were irradiated at SRP, 1 (14) used for flow tests, and 1 (16) used for HWCTR zero power tests. The remaining three tubes were cut up for evaluation and other uses. Data for tubes 11, 14, 15 and 16 are presented below.

A. Description

Thick-wall tube, 2.060" OD X 0.297" wall (nominal)

B. Composition

Core: U-2 w/o Zr alloy.
Cladding: Zircaloy-2 (15 mils).
End seals: Integral-type Zircaloy-2

C. Dimensions

Taken before final bright-etching (ID should be increased 0.002" and OD decreased by 0.002"). Tube 16 after etching and before heat treatment.

| | Tube 11 (inches) | Tube 14 (inches) | Tube 15 (inches) | Tube 16 (Inches) |
|---|---|---|---|---|
| Over uniform core, OD | 2.065 | 2.064 | 2.064 | 2.055 |
| ID | 1.470 | 1.468 | 1.472 | 1.456 |
| Over end seals, OD | 2.073 | 2.077 | 2.072 | 2.076 |
| ID | 1.476 | 1.475 | 1.477 | 1.474 |
| Overall length | 132-1/8 | 132-1/4 | 132-1/4 | 132-1/4 |
| Core, tip-to-tip | 117-3/8 | 118-3/8 | 119-5/8 | 119-9/16 |

D. Extrusion Conditions

(Done at Revere Copper & Grass Co., Detroit, Michigan)

| | Tube 11 | Tube 14 | Tube 15 | Tube 16 |
|---|---|---|---|---|
| NM extrusion number | 16241 | 16244 | 16431 | 16432 |
| Tool temperature (°C) | 540 | 540 | 540 | 540 |
| Billet temperature (°C) | 650 | 650 | 650 | 650 |
| Extrusion force, running (tons) | 1800 | 1850 | 2200 | 1900 |
| Extrusion force, max. (tons) | 2100 | 2050 | 2350 | 2200 |
| Ram speed (inches/min) | 25 | 25 | 25 | 25 |

Billets, copper-clad
Copper cutoff

E. Heat Treatment

No. 11 held at 800 °C for ½ hour supported by Mo pads; rapid cool.
No. 14 held at 880 °C for 7 hours wrapped in Ta foil; rapid cool. Tantalum stuck to Zircaloy cladding causing indentations and pits.
No. 15 held at 880 °C for 7 hours supported by Mo pads; rapid cool.
No. 16 held at 890 °C for 7 hours supported by type 304 stainless steel; rapid cool.

F. Autoclave Test

No. 11 tested for 24 hours at 345 °C in water. Black tarnish film with a few white spots near end.
No. 14 tested for 24 hours at 345 °C in water. White spots running length of cladding attributed to faulty rinsing of etching solution.
No. 15 tested for 24 hours at 345 °C in water. General black tarnish film with some white spots.

G. Remarks

None.

H. Current Conditions

Tubes 14 and 16 are stored at SRL. No. 14 may be suitable for irradiation; No. 16 is not.

4. NM Tube Nos. 17-21

Ref: (1) Progress Reports NMI-4359, 4361, 4366.

(2) NMI-4365, 7/24/58, J. L. Klein, "Evaluation of Zircaloy-clad U-2 w/o Zr Alloy Tube No. 19, Extrusion No. 16819".

Three of the five tubes were sent to SRL, two (18 and 20) were used for HWCTR zero power tests, and one (19) was irradiated at SRP. Tube No. 20 was used as a demonstration tube and for trial handling runs in Canada before being sent to SRL. The remaining two tubes were cut up for evaluation and other uses. Data for tubes 18, 19 and 20 are presented below.

A. Description

Thick-wall tube, 2.060" OD X 0.297" wall (nominal).

B. Composition

Core: U-2 w/o Zr alloy.
Cladding: Zircaloy-2 (15 mils)
End seals: Integral-type Zircaloy-2

C. Dimensions

Taken before final bright-etching (ID should be increased ~0.002" and OD decreased by ~0.002"). Tube 18 after etching and before heat treatment.

| | Tube 18 (inches) | Tube 19 (inches) | Tube 20 (inches) |
|---|---|---|---|
| Over uniform core, OD | 2.054 | 2.063 | 2.058 |
| ID | 1.456 | 1.468 | 1.467 |
| Over end seals, OD | 2.070 | 2.070 | 2.066 |
| ID | 1.472 | 1.476 | 1.472 |
| Overall length | 132 | 132 | 132 |
| Core, tip-to-tip | - | 119 | - |

D. Extrusion Conditions

(Done at Revere Copper & Brass Co., Detroit, Michigan)

| | Tube 18 | Tube 19 | Tube 20 |
|---|---|---|---|
| NM extrusion number | 16818 | 16819 | 16820 |
| Tool temperature (°C) | - | 540 | - |
| Billet heat temp. (°C) | - | 650 | - |
| Extrusion force, running (tons) | 1875 | 1875 | 1925 |
| " " , maximum " | 2200 | 2275 | 2150 |
| Ram speed (inches/min) | - | 25 | - |
| Extrusion constant, running (tsi) | 19.7 | 19.7 | 20.2 |
| Extrusion ratio | 18.3 | 18.3 | 18.3 |
| Billets, copper-clad | | | |
| Copper cutoff | | | |

E. Heat Treatment

No. 19 held at 890 °C for 7 hours supported by a ground, type 304 stainless steel angle; rapid cool.

No. 20 held at 880 °C for 7 hours supported by Mo pads followed by water quenching.

F. Autoclave Test

No. 19 tested for 24 hours at 345 °C in water followed by 24 hours at 400 °C in 1500 psi steam. Hard, lustrous, black oxide film formed.

No. 20 tested for 24 hours at 345 °C in water, followed by 24 hours at 400 °C in 1500 psi steam. Satisfactory corrosion resistance shown.

G. Remarks

None.

H. Current Condition

Nos. 18 and 20 are stored at SRL. Neither is considered suitable for irradiation.

5. NM Tube Nos. 22-32

Ref: (1) Progress Reports NMI-4361, 4363, 4366, 4381, 4382, 4383.

(2) NMI-4374, 2/13/59, D.F.Kaufman and R.G.Jenkins, "Evaluation of Zircaloy-Clad U-2 w/o Zr Alloy Tube No. 22".

(3) NMI-4375, 2/19/59, D.F.Kaufman and R.G.Jenkins, "Evaluation of Zircaloy-Clad U-2 w/o Zr Alloy Tube No. 23".

(4) NMI-4376, 2/26/59, D.F.Kaufman and R.G.Jenkins, "Evaluation of Zircaloy-Clad U-2 w/o Zr Alloy Tube No. 25".

(5) NMI-4372, 1/9/59, D.F.Kaufman and R.G.Jenkins, "Evaluation of Zircaloy-Clad U-2 w/o Zr Alloy Tube No. 26".

(6) NMI-4377, 4/13/59, D.F.Kaufman and R.G.Jenkins, "Evaluation of Zircaloy-Clad U-2 w/o Zr Alloy Tube No. 28".

(7) NMI-4377--Supplement, 7/29/60, D.F.Kaufman, R.G.Jenkins, W.B.Tuffin, "Spheroidization Heat Treatment and Re-evaluation of Zircaloy-Clad U-2 w/o Zr Alloy Tube No. 28".

(8) NMI-4370, 12/16/58, D.F.Kaufman and R.G.Jenkins, "Complete Set of Tables for Power Tube No. 29".

(9) NMI-4371 (Rev.), 12/23/58, D.F.Kaufman and R.G.Jenkins, "Evaluation of Zircaloy-Clad U-2 w/o Zr Alloy Tube No. 30".

(10) NMI-4373, 1/12/59, D.F.Kaufman and R.G.Jenkins, "Evaluation of Zircaloy-Clad U-2 w/o Zr Alloy Tube No. 31".

(11) NMI-4378, 4/13/59, D.F.Kaufman and R.G.Jenkins, "Evaluation of Zircaloy-Clad U-2 w/o Zr Alloy Tube No. 32".

To demonstrate a prototype semi-production operation for manufacture of co-extruded, long, tubular fuel elements, a total of 11 tubes was scheduled--an initial run of 2 tubes followed by a group of 9 tubes. This group of tubes was the first to be scheduled at American Brass Co. (ABC). These and all subsequent thick-walled tubes were extruded at ABC primarily because of close location.

The first 2 tubes (22 and 23) were extruded on schedule; only 4 of the remaining 9 were on schedule; 2 (26 and 28) extruded successfully and 2 (24 and 27) unsuccessfully. All of the remaining 5 prototype tubes (25, 29 -32) were later successfully extruded after modification of billet handling procedures at ABC.

Of the 11 tubes in this program, 4 (22,28,29,30) were irradiated at SRP; 3 (26,31,32) were used for HWCTR zero power tests and are stored at SRL; and the remaining 4 (23,24,25,27) were cut up for evaluation and other uses. Data for the irradiated tubes and those stored at SRL are presented below.

A. Description

Thick-wall tubes, 2.060" OD X 0.297" wall (nominal). Drawing STD-MDX-4-1598, Rev. 3.

B. Composition

Core: U-2 w/o Zr alloy.

Cladding: Zircaloy-2 (15 mils).

End seals: Integral-type Zircaloy-2.

C. Dimensions

Taken before final bright-etching. ID should be increased ~0.002" and OD decreased ~0.002".

| | Tube Numbers | | | | | | |
|---|---|---|---|---|---|---|---|
| | 22 (in.) | 26 (in.) | 28 (in.) | 29 (in.) | 30 (in.) | 31 (in.) | 32 (in.) |
| Over uniform core, OD | 2.067 | 2.071 | 2.064 | 2.064 | 2.069 | 2.065 | 2.066 |
| " " " , ID | 1.468 | 1.469 | 1.467 | 1.468 | 1.468 | 1.466 | 1.468 |
| Over end seals, OD | 2.075 | 2.081 | 2.075 | 2.075 | 2.077 | 2.075 | 2.079 |
| " " " , ID | 1.473 | 1.471 | 1.472 | 1.472 | 1.472 | 1.472 | 1.473 |
| Overall length | $132\frac{1}{16}$ | 132 | 132 | 132 | 132 | 132 | 132 |
| Core, tip-to-tip | $115\frac{3}{4}$ | $113\frac{13}{16}$ | $115\frac{3}{8}$ | $115\frac{7}{8}$ | $115\frac{5}{16}$ | $115\frac{9}{16}$ | $116\frac{1}{16}$ |

D. Extrusion Conditions

(Done at American Brass Co.)

| | Tube Numbers | | | | | | |
|---|---|---|---|---|---|---|---|
| | 22 | 26 | 28 | 29 | 30 | 31 | 32 |
| NM extrusion number | 18393 | 18386 | 18388 | 18389 | 18390 | 18391 | 18392 |
| Tool temperature (°C) | 430-480(1) | 430-480 | 430-480 | 430-480 | 430-480 | 430-480 | 430-480 |
| Billet temp. (°C) | 645 | 665 | 660 | 650 | 650 | 650 | 650 |
| Extrusion force, running (tons) | 1630 | 1630 | 1670 | 1600 | 1600 | 1600 | 1600 |
| Extrusion force, maximum (tons) | 1800 | 1730 | 1800 | 1770 | 1800 | 1880 | 1880 |
| Ram speed (inches/min) | 25 | 25 | 25 | 25 | 25 | 25 | 25 |
| Extrusion constant, running (tsi) | 17.1 | 17.1 | 17.5 | 16.8 | 16.8 | 16.8 | 16.8 |
| Extrusion ratio | 18.3 | 18.3 | 18.3 | 18.3 | 18.3 | 18.3 | 18.3 |
| Billets, copper-clad | | | | | | | |
| Copper cutoff | | | | | | | |

(1) Liner at 430 °C; die and mandrel at 480 °C.

E. Heat Treatment

Tubes 22, 26, 29, 30 and 32 were held at 890 °C for 7 hours supported by a graphite strip-lined stainless steel angle; rapid cool (water quenching of evacuated tube container).

No. 28 held at 890 °C for 9 hours; rapid cool. Following autoclaving, this tube received a spheroidization heat treatment at New England Metallurgical Corp. The tube was held in the range 670-695 °C for 72 hours, and rapid cooled by quenching the evacuated container in a 4% caustic solution.

No. 31 held at 890 °C for 9 hours and rapid cooled.

F. Autoclave Test

All 7 tubes were tested for 24 hours at 345 °C in water followed by 24 hours at 400 °C in 1500 psi steam. All tubes had a continuous, hard, lustrous, black oxide film associated with Zircaloy having good corrosion resistance to high temperature water.

G. Remarks

None.

H. Current Condition

Nos. 26, 31 and 32 are stored at SRL. All three tubes are considered suitable for irradiation.

6. NM Tube Nos. 33-42

Ref: (1) Progress Reports NMI-4369, 4381, 4382, 4383, 4384, 4385, 4386, 4392, 4393.

(2) NMI-4389, 6/2/59, D.F.Kaufman and W.J.Richmond, "Evaluation of Zircaloy-Clad U-2 w/o Zr Alloy Tube No. 36".

(3) NMI-4387, 6/10/59, D.F.Kaufman and W.J.Richmond, "Evaluation of Six Zircaloy-Clad U-2 w/o Zr Alloy Tubes Made for Irradiation in the VBWR Test Loop (37-42)".

(4) NMI-4380, 1/7/59, W.J.Richmond and D.F.Kaufman, "Evaluation of Zircaloy-Clad U-2 w/o Zr Alloy Tube No. 34".

A group of ten fuel tubes was fabricated as part of a program to provide an irradiation candidate for testing in the General Electric Boiling Water Test Reactor (VBWR), Vallecitos, California.

The first four tubes (33-36) used natural uranium and served as prototypes. Of these, one (34) was irradiated at SRP and one (35) was used for SRL flow tests.

The second group of tubes (37-42) used uranium enriched to 3.06% $^{235}U$. No. 42 was irradiated at VBWR; No. 38 was destructively evaluated. The remaining four tubes, three of which are suitable for irradiation, are stored at SRL.

Data for one of the natural uranium tubes (34) and five of the enriched tubes are presented below.

A. Description

Thick-wall tubes designed for use in the VBWR, 2.060" OD X 0.297" wall (nominal). Drawing ST-MDX-2253.

B. Composition

Core: U-2 w/o Zr alloy.
Tubes 37-42, U enriched to 3.06% $^{235}U$.

Cladding: Zircaloy-2 (15 mils).

End seals: Integral-type Zircaloy-2.

C. Dimensions

Taken before final bright-etching. (ID should be increased ~0.003 and OD decreased by ~0.003".

| | Tube Numbers | | | | | |
|---|---|---|---|---|---|---|
| | 34 (in.) | 37 (in.) | 39 (in.) | 40 (in.) | 41 (in.) | 42 (in.) |
| Over uniform core, OD | - | 2.069 | 2.066 | 2.066 | 2.066 | 2.067 |
| " " " ID | - | 1.470 | 1.466 | 1.465 | 1.467 | 1.467 |
| Over end seals, OD | - | 2.082 | 2.079 | 2.080 | 2.078 | 2.081 |
| " " " ID | - | 1.477 | 1.474 | 1.474 | 1.475 | 1.475 |
| Overall length | 44 | 43-15/16 | 44 | 44 | 43-31/32 | 44 |
| Core, tip-to-tip | 33-3/4 | 35 | 34 | 34 5/16 | 34 1/4 | 34 |

D. Extrusion Conditions

(Done at American Brass Co.)

| | Tube Numbers | | | | | |
|---|---|---|---|---|---|---|
| | 34 | 37 | 39 | 40 | 41 | 42 |
| NM extrusion number | 19658 | 19889 | 19891 | 19892 | 19893 | 19894 |
| Tool temperature (°C) | 430-480(1) | 430-480 | 430-480 | 430-480 | 430-480 | 430-480 |
| Billet temperature (°C) | 655 | 650 | 645 | 650 | 650 | 650 |
| Extrusion force, running (tons) | 1550 | 1770 | 1530 | 1570 | 1520 | 1500 |
| Extrusion force, maximum (tons) | 1760 | 1900 | 1690 | 1640 | 1670 | 1670 |
| Ram speed (inches/min) | 25 | 25 | 25 | 25 | 25 | 25 |
| Extrusion constant, running (tsi) | 16.4 | 17.0 | 16.0 | 16.4 | 15.9 | 15.7 |
| Extrusion ratio | 18.3 | 18.3 | 18.3 | 18.3 | 18.3 | 18.3 |
| Billets, copper-clad | | | | | | |
| Copper cutoff | | | | | | |

E. Heat Treatment

All tubes were held at 890 °C for 7 hours and rapid-cooled.

F. Autoclave Test

Nos. 34, 37, 39-42 were tested for 24 hours at 345 °C in water followed by 24 hours at 400 °C in 1500 psi steam. There was no evidence of bond-line corrosion at the tube ends after autoclaving. Only tube 39 had white oxide after autoclaving; all others showed lustrous black oxide.

G. Remarks

No. 34 failed during irradiation at SRP.

No. 41 was irradiated to 1200 MWD/T in the VBWR.

H. Current Condition

Tube Nos. 35, 37, 39, 40, 41 (irradiated in VBWR) and 42 are stored at SRL. Tubes 35 and 37 are considered unsuitable for irradiation.

Tube Nos 33 and 36 are stored at NM.

---

(1) Liner at 430 °C; die and mandrel at 480 °C.

7. NM Tube Nos. 44-49

Ref: Progress Reports NMI-4383, 4384, 4385, 4386, 4392, 4393, 4394.

A group of six prototype tubes was fabricated to develop a process for production of driver tubes for HWCTR. All but one (44, used for flow tests) were destructively evaluated. Data for tube 44 are presented below.

A. Description

Prototype HWCTR driver tubes, 2.300" OD X 0.167" wall (nominal).

B. Composition

Core: Zr-9.3 w/o U alloy.

Cladding: Zircaloy-2 (15 mils).

End seals: Integral-type Zircaloy-2.

C. Dimensions

No. 44 was cold-drawn from its as-extruded size of 2.367" OD X 1.976" ID to 2.308" OD X 1.964" ID in two passes.
Overall length: 118".
Core length, tip-to-tip: 99-15/16"
Bottom end seal length (front as-extruded): 2".

D. Extrusion Data

Not reported.

E. Heat Treatment

None.

F. Autoclave Test

None.

G. Remarks

Based on the 11.2% cold-drawing of tube 44 to size, as determined from length measurements, cold-drawing has been eliminated from the process, with all future tubes extruded to size.

H. Current Condition

Tube 44 is stored at SRL.

8. NM Tube Nos. 50-55

Ref: (1) Progress Reports NMI-4392, 4393, 4394, 4395, 4396, 4397, 4398, 7221.

(2) NMI-4394, 11/19/59, W.L.Larson, "Evaluation of Zircaloy-Clad Unalloyed Uranium Tube No. 53".

To broaden the base of the power tube irradiation program at SRP, NM fabricated a group of 5 dingot-base unalloyed uranium tubes, similar in dimensions to the previous U-2 w/o Zr cored power tubes. One tube, No. 53, was irradiated at SRP. Data for No. 53 are presented below.

A. Description

Unalloyed U thick-wall tubes, 2.060" OD X 0.297" wall (nominal).

B. Composition

Core: Unalloyed U.

Cladding: Zircaloy-2 (30 mils).

End seals: Integral-type Zircaloy-2.

C. Dimensions

Taken before final bright-etching. (ID should be increased ~0.003" and OD decreased ~0.003".)

| | Tube 53 (inches) |
|---|---|
| Over uniform core, OD | 2.057 |
| " " " , ID | 1.469 |
| Over end seals, OD | 2.070 |
| " " " , ID | 1.475 |
| Overall length | 132 |
| Core, tip-to-tip | 108¼ |

D. Extrusion Conditions

(Done at American Brass Co.)

| | Tube 53 |
|---|---|
| NM extrusion number | 20921 |
| Tool temperature (°C) | 430-480(1) |
| Billet temperature (°C) | 630 |
| Extrusion force, running (tons) | 912 |
| " " , maximum (tons) | 1088 |
| Extrusion constant, running (tsi) | 15.9 |
| Ram speed (inches/min) | 25 |
| Extrusion ratio | 12.7 |
| Billets, copper-clad | |
| Copper cutoff | |

(1) Liner at 430°C; die and mandrel at 480°C.

E. Heat Treatment

Heat treatment was done at the Hick Corporation, Hyde Park, Mass., using a Holden Type-701 vertical salt bath furnace. The tube, in its copper jacket, was immersed in a 730 °C salt bath for 10 minutes, air-cooled to 200 °C, then water-quenched.

F. Autoclave Test

No. 53 was tested for 4 hours at 345 °C in water followed by 6 hours at 400 °C in 1500 psi steam. A continuous, hard, lustrous, black oxide film resulted. The insurance welds at the tube ends had a white oxide layer.

G. Remarks

Tube 55 was extruded from a tandem billet containing two short cores, one with high carbon and one with low carbon, for characterization of the full-length tubes.

Because of inferior bond quality at the integral end seals of No. 53, insurance welds were made at both tube ends at the end-seal-cladding interfaces.

No. 51 was used for HWCTR zero power tests.

H. Current Condition

Tube 51 is stored at SRL, and tubes 54 and 55-A are stored at NM. None of these tubes are suitable for irradiation.

9. NM Tube Nos. 56-60

Ref. (1) Progress Reports NMI-4395, 4396, 4397.

(2) NMI-4379, 4/26/60, A.M.Huntress and D.F.Kaufman, "Evaluation of Three Enriched HWCTR Driver Tubes for Irradiation at SRP (58-60)."

A second group of five prototype HWCTR, two natural U (56,57) and three enriched (58-60), were fabricated to obtain enriched tubes for irradiation tests at SRP. This second group of prototypes differed from the first set (Item 7 of this Appendix) in their being extruded directly to size rather than 15% oversize for subsequent cold-drawing to size. Two of these enriched tubes (59, 60) were irradiated at SRP with the third (58) used as a Nuclear Test Gage (NTG) standard. The two natural U tubes were used to evaluate core length. Data for the enriched tubes are presented below.

A. Description

Prototype HWCTR driver tubes, 2.300" OD X 0.167" wall (nominal).

Drawing STD-MDX4-2346.

B. Composition

Core: Zr-9.3 w/o U alloy (Nos. 58-60, U enriched to 93% $^{235}U$).

Cladding: Zircaloy-2 (15 mils).

End seals: Integral-type Zircaloy-2.

C. Dimensions

Taken before final bright-etching. (ID should be increased 0.003" and OD decreased by 0.003".)

| | Tube Numbers | | |
|---|---|---|---|
| | 58 (inches) | 59 (inches) | 60 (inches) |
| Over uniform core, OD | 2.302 | 2.300 | 2.298 |
| " " " , ID | 1.961 | 1.961 | 1.961 |
| Over end seals, OD | 2.302 | 2.300 | 2.298 |
| " " " , ID | 1.960 | 1.960 | 1.960 |
| Overall length | 118 | 118 | 118 |
| Core, tip-to-tip | 112-3/16 | 112-1/4 | 112-3/8 |

D. Extrusion Conditions

(Done at American Brass Co.)

| | Tube Numbers | | |
|---|---|---|---|
| | 58 | 59 | 60 |
| NM extrusion number | 21336 | 21337 | 21338 |
| Tool temperature (°C) | 430-480 (1) | 430-480 | 430-480 |
| Billet temperature (°C) | 690 | 690 | 690 |
| Extrusion force, running (tons) | 1250 | 1170 | 1210 |
| Extrusion force, maximum (tons) | 1330 | 1290 | 1330 |
| Extrusion constant, running (tsi) | 20.6 | 19.3 | 20.0 |
| Ram speed (inches/min) | 25 | 25 | 25 |
| Extrusion ratio | 17.1 | 17.1 | 17.1 |
| Billets, copper-clad | | | |
| Copper cutoff | | | |

(1) Liner at 430 °C; die and mandrel at 480 °C.

E. Heat Treatment

None.

F. Autoclave Test

The three enriched tubes were tested for 4 hours at 345 °C in water followed by 4 hours at 400 °C in 1500 psi steam. A lustrous, black oxide resulted.

G. Remarks

Tube 58 was not suitable for irradiation because of clad thinning in scored areas of 2 to 6 mils (minimum clad specification - 10 mils). Tube was utilized as a standard for the Nuclear Test Gage at SRP.

H. Current Condition

Tube 58 is stored at SRL; it is not suitable for irradiation.

10. NM Tube Nos. 61-63

Ref: Progress Reports NMI-4395, 4396, 4397, 7221, 7222, 7223.

To produce experimental power tubes with uranium alloys other than U-2 w/o Zr, a group of three tubes was fabricated. Two of the tubes were full-length, one with a core of U-1 w/o Si (62) and the other with a core of U-1.5 w/o Mo (63). The third tube (61A, 61B) was a tandem extrusion containing a short core of each of the two compositions used for destructive evaluation to characterize the full-size tubes. Data for the full-length tubes used for HWCTR zero power test are presented below.

A. Description

Thick-wall tubes, 2.060" OD X 0.297" wall (nominal).

B. Composition

Core (61A and 62): U-1 w/o Si.
(61B and 63): U-1.5 w/o Mo.

Cladding: Zircaloy-2 (15 mils).

End seals: Integral-type Zircaloy-2.

C. Dimensions

Not reported.

D. Extrusion Conditions

Not reported.

E. Heat Treatment

Tube 62 was beta-treated in a salt bath for 10 minutes at 730°C and air-cooled in its copper extrusion jacket.

Tube 63 received no heat treatment.

F. Autoclave Test

None.

G. Remarks

Several depressions up to 6½ mils deep were observed on the OD over the uniform core of Tube 62. Clad thinning on the inner surface near the rear end seal was observed on Tube 63. Neither tube was considered suitable for irradiation.

H. Current Condition

Tubes 62 and 63 are stored at SRL. They are not suitable for irradiation.

11. NM Tube Nos. 64-69

Ref: (1) Progress Reports NMI-4398, 7221, 7222, 7223, 7224.

(2) NMI-7200, 4/25/60, W.L.Larson, "Evaluation of Zircaloy-Clad Unalloyed Uranium Tubes Made For Irradiation in the VBWR Test Loop (68,69)".

This group of thick-wall tubes consisted of four short natural U prototypes (64-67) to investigate the effect of billet end shapes on clad thinning and two enriched U tubes (68,69) for irradiation testing at the VBWR. The four prototype tubes were destructively evaluated. Although the two enriched tubes are suitable for irradiation, they were not used and are currently stored at SRL. Data for the enriched tubes are presented below.

A. Description

Thick-wall VBWR tubes, 2.060" OD X 0.297" wall (nominal).
Drawing MDX4-2253.

B. Composition

Core: Unalloyed U (68, 69 - U enriched to 3.10% $^{235}U$)
Cladding: Zircaloy-2 (30 mils).
End seals: Integral-type zirconium.

C. Dimensions

Taken before final bright-etching. (ID should be increased 0.003" and OD decreased by 0.003".)

| | Tube 68 (inches) | Tube 69 (inches) |
|---|---|---|
| Over uniform core, OD | 2.067 | 2.066 |
| " " " , ID | 1.468 | 1.467 |
| Over end seals, OD | 2.082 | 2.080 |
| " " " , ID | 1.472 | 1.469 |
| Overall length | 50 | 50 |
| Core, tip-to-tip | 39-5/8 | 40-1/2 |

D. Extrusion Conditions

(Done at American Brass Co.)

| | Tube 68 | Tube 69 |
|---|---|---|
| NM extrusion number | 27323 | 27324 |
| Tool temperature (°C) | 430-480(1) | 430-480 |
| Billet temperature (°C) | 630 | 630 |
| Extrusion force, running (tons) | 1230 | 1260 |
| " " , maximum (tons) | 1660 | 1650 |
| Extrusion constant, running (tsi) | 12.9 | 13.2 |
| Ram speed (inches/min) | 25 | 25 |
| Extrusion ratio | 18.3 | 18.3 |
| Billets copper-clad | | |
| Copper cutoff | | |

E. Heat Treatment

Both enriched tubes were beta-treated in a salt bath for 10 minutes at 700°C and air-cooled in their copper extrusion jackets.

F. Autoclave Test

The two tubes were tested for 4 hours at 345°C in water followed by 4 hours at 400°C in 1500 psi steam. Both tubes exhibited a continuous, hard, lustrous, black oxide film with no white oxide observed.

G. Remarks

Four different core end shape designs were extruded (64,67) to obtain the design used for the two enriched tubes. The core end shape selected had six-degree compensated front and rear end shapes; single tooth in middle of front and rear end seal walls interlocking with core; also 1/8-inch, 10° chamfers on all four corners of core.

---

(1) Liner at 430°C; die and mandrel at 480°C.

Both enriched tubes had clad thinning on the OD near the end seals (0.011" versus a specified 0.030 ± 0.003"). However, both tubes were considered suitable for irradiation testing.

H. Current Condition

Tubes 68 and 69 are stored at SRL and are considered suitable for irradiation.

12. NM Tube Nos. 70-71

Ref: Progress Reports NMI-7224, 7225, 7226.

Two thick-wall tubes (2.060" OD X 0.297" wall) having different core compositions, U-1 w/o Si (70) and U-1.5 w/o Mo (71), were fabricated as prototypes for production of similar tubes for the VBWR. Both tubes were destructively evaluated.

Work on thick-wall tubes was discontinued because of a design change from single thick-wall power tubes to a two concentric thin-wall tube design. As a result of this design change no detailed data on tubes 70 and 71 were reported.

13. NM Tube Nos. 72-73

Ref: Progress Reports NMI-7224, 7225, 7226.

Two prototype thick-wall tubes were fabricated with unalloyed U cores to develop irradiation candidates at SRP or at Chalk River in the NRU. Tube 73 was destructively evaluated, and tube 72 was processed and shipped to Chalk River where it was irradiated in NRU.

As a result of the design change to concentric thin-wall power fuel tubes, development of thick-wall tubes was discontinued with these two tubes. Data on tube 72 are presented below.

A. Description

Thick-wall tube, 2.060" OD X 0.297" wall (nominal).

B. Composition

Core: Unalloyed U

Cladding: Zircaloy-2 (30 mils)

End seals: Integral-type Zircaloy-2

C. Dimensions

None reported.

D. Extrusion Conditions

(Done at American Brass Co.)

No data reported.

E. Heat Treatment

Both tubes were beta-heat treated in a salt pot at SRL while still in their copper extrusion jackets.

F. Autoclave Test

Tube 72 was tested for 4 hours at 345 °C in water followed by 4 hours at 400 °C in 1500 psi steam. A lustrous, black film resulted. Tube 73 was not autoclaved.

G. Remarks

Tube 72 had outer clad thinning of 9 mils at the front end of the core as determined by autoradiography.

H. Current Condition

Disposition of tube 72 following irradiation in NRU is unknown.

14. NM Tube Nos. 74A, 74B, 74-76

Ref: (1) Progress reports NMI-7226, 7227, 7228

(2) NMI-7202, 12/27/60, H.F.Sawyer, "Evaluation of Zircaloy-4 Clad Unalloyed Uranium Outer Tube No. 74 Made for Flow-Testing at SRP, Extrusion No. 27944".

(3) NMI-7203, 12/14/60, H.F.Sawyer, "Evaluation of Zircaloy-4 Clad Unalloyed Uranium Outer Tube No. 75, Extrusion No. 27943, Made for Irradiation at Savannah River".

Five tubes were fabricated in this first group of thin-wall outers (2.060" OD X 0.180" wall), two (74A and 74B) to evaluate core preshapes, two full-length (118") tubes (74, 75), and one short (50") tube (76). Tube 74 was used for flow testing and tube 75 irradiated at SRP. Destructive evluation of tube 76, a VBWR prototype, was done at NM. Data for tubes 74 and 75 are presented below.

A. Description

Thin-wall tubes, 2.060" OD X 0.180" wall (nominal).

B. Composition

Core: Unalloyed U

Cladding: Zircaloy-4 (25 mils)

End seals: Integral-type zirconium

C. Dimensions

Taken before final bright-etching. (ID should be increased 0.003" and OD decreased by 0.003".)

| | Tube 74 (inches) | Tube 75 (inches) |
|---|---|---|
| Over uniform core, OD | 2.055 | 2.065 |
| " " " , ID | 1.684 | 1.694 |
| Over end seals, OD | 2.069 | 2.070 |
| " " " , ID | 1.697 | 1.696 |
| Overall length | 118 | 118 |
| Core, tip-to-tip | 105 | 103.9 |

D. Extrusion Conditions

(Done at Nuclear Metals.)

| | Tube 74 | Tube 75 |
|---|---|---|
| NM extrusion number | 27944 | 27943 |
| Tool temperature (°C) | 480 | 480 |
| Billet temperature (°C) | 630 | 630 |
| Extrusion force, running (tons) | 755 | 795 |
| Extrusion force, maximum (tons) | 1025 | 1100 |
| Extrusion constant, running (tsi) | 15.6 | 16.4 |
| Ram speed (inches/min) | 15 | 15 |
| Extrusion ratio(1) | 15.1 | 15.1 |

Billets, copper-clad
Copper cutoff

E. Heat Treatment

Tube 74 was not heat treated.

Beta heat treatment of tube 75 in its copper extrusion jacket was performed at Atlas Steels, Ltd., Welland, Ontario, using a 15-inch ID by 16-foot deep salt bath. The tube was held in the 730°C salt for 10 minutes, air-cooled for 5½ minutes, then water-quenched. The tube was rotated at 15 rpm to help prevent distortion during the operation.

(1) Based on tool sizes.

F. Autoclave Test

Both tubes were tested for 4 hours at 345 °C in water followed by 4 hours at 400 °C in 1500 psi steam. A continuous, hard, lustrous, black oxide film was observed on both tubes.

G. Remarks

The angular preshape used in tube 74A produced more uniform cladding in the taper region than the spherical preshapes of tube 74B. Angular preshapes were subsequently used.

H. Current Condition

Tube 74 is stored at SRL and is not a suitable candidate for irradiation.

15. NM Tube Nos. 77-83

Ref: (1) Progress Reports NMI-7226, 7227, 7228.

(2) NMI-7204, 11/20/61, W.J.Richmond, "Evaluation of Zircaloy-4 Clad U-1 w/o Si, Tube No. 79".

(3) NMI-7212, 12/21/61, W.J.Richmond, "Evaluation of Zircaloy-4 Clad U-1.5 w/o Mo Tubes No. 82 and No. 83".

(4) NMI-7212 Supplement, 2/15/63, W.J.Richmond, "Completion of Evaluation of Zircaloy-Clad U-1.5 w/o Mo Tube No. 83".

To produce VBWR enriched thin-wall tubes for irradiation tests, a group of four natural U prototypes and three enriched U (3% $^{235}U$) were fabricated. One of the natural U tubes (77) and one enriched U tube (79) were alloyed with 1 w/o Si. The remaining three natural U tubes (78, 80, 81) and two enriched tubes (82, 83) were alloyed with 1.5 w/o Mo. The four natural U tubes were destructively evaluated. Tubes 79 and 83 are both suitable for irradiation test and are stored at SRL. Tube 82 was irradiated in the HWCTR. Data for the three enriched U tubes are presented below.

A. Description

Thin-wall tubes, 2.060" OD X 0.180" wall nominal for the VBWR.

B. Composition

Core: Tube 77 - U-1 w/o Si
" 79 - U-1 w/o Si (U enriched to 3% $^{235}U$)
" 78,80,81 - U-1.5 w/o Mo
" 82,83 - U-1.5 w/o Mo (U enriched to 3% $^{235}U$)

Cladding: Zircaloy-4 (25 mils)

End seals: Integral-type zirconium (Zircaloy-4 for tubes 77 and 79)

C. Dimensions

Taken before final bright-etching. (ID should be increased 0.003" and OD decreased by 0.003".)

| | Tube Numbers | | |
|---|---|---|---|
| | 79 (inches) | 82 (inches) | 83 (inches) |
| Over uniform core, OD | 2.072 | 2.072 | 2.071 |
| " " " , ID | 1.699 | 1.695 | 1.696 |
| Over end seals, OD | 2.081 | 2.080 | - |
| " " " , ID | 1.707 | 1.701 | - |
| Overall length | 50 | 50 | 44-11/16 |
| Core, Tip-to-tip | 41-3/4 | 42-1/2 | 43-1/4 |

D. Extrusion Conditions
(Done at American Brass Co.)

| | Tube 79 | Tube 82 | Tube 83 |
|---|---|---|---|
| NM extrusion number | 28553 | 29115 | 29116 |
| Tool temperature (°C) | 430-480(1) | 430-480 | 430-480 |
| Billet temperature (°C | 649 | 632 | 632 |
| Extrusion force, running (tons) | 1280 | 1120 | 1140 |
| " " , maximum (tons) | 1360 | 1200 | 1320 |
| Extrusion constant, running (tsi) | 20.0 | 17.5 | 17.8 |
| Ram speed (inches/min) | 25 | 25 | 25 |
| Extrusion ratio | 18.3 | 18.3 | 18.3 |

Billets copper-clad
Copper cutoff

E. Heat Treatment

Tube 79 was immersed in a triple chloride salt bath at 740°C for 10 minutes followed by air-cooling in its copper extrusion jacket.

---

(1) Liner at 430°C; die and mandrel at 480°C.

Tubes 82 and 83 were each placed in an evacuated steel container in a graphite-lined stainless steel angle support fixture and heat treated at 775 °C for 15 minutes, furnace-cooled to 535 °C, held 1 hour, then air-cooled. This heat treatment was developed to give extruded material a microstructure resembling that of as-cast material.

F. Autoclave Test

Tubes 79 and 82 were tested for 4 hours at 345 °C in water followed by 4 hours at 400 °C in 1500 psi steam. Both tubes exhibited a continuous, hard, black oxide surface.

Tube 83 was tested for 4 hours at 345 °C in water followed by 32 hours at 400 °C in 1500 psi steam. A continuous, hard, black oxide surface film resulted.

G. Remarks

None.

H. Current Condition

Tubes 79 and 83 are stored at SRL and are suitable for irradiation testing.

16. NM Tube Nos. 84-99, 106, 113

Ref: (1) Progress Reports NMI-7227, 7228, 7229, 7230, 7231, 7232, 7233, 7234.

(2) NMI-7208, 4/24/61, H.F.Sawyer and E.F.Jordan, "Evaluation of the Prototype Set of Zircaloy-4 Clad Unalloyed Uranium Outer Tubes Nos. 95 and 97, Extrusions No. 28965 and No. 28967".

A group of 18 tube extrusions were made to obtain basic information for fabrication of thin-wall outer tubes using unalloyed uranium cores. Fifteen of these tubes were of full length (118") with the three remaining tubes (98, 106, 113) being of short length (50") for the VBWR.

Two of the long tubes (95, 97) were flow tested at SRL; a third (96) was damaged during extrusion; and the remaining 15 tubes were destructively evaluated. Data for tubes 95 and 97 are presented below.

A. Description

Thin-wall tubes, 2.060" OD X 0.180" wall (nominal).

B. Composition

Core: Unalloyed uranium

Cladding: Zircaloy-4 (25 mils)

End seals: Integral-type, zirconium

C. Dimensions

Taken before final bright-etching. (ID should be increased 0.003" and OD decreased by 0.003".)

| | Tube 95 (inches) | Tube 97 (inches) |
|---|---|---|
| Over uniform core, OD | 2.060 | 2.062 |
| " " " , ID | 1.699 | 1.696 |
| Over end seals, OD | 2.068 | 2.074 |
| " " " , ID | 1.699 | 1.701 |
| Overall length | 118 | 118 |
| Core, tip-to-tip | 111.6 | 111.0 |

D. Extrusion Conditions

| | Tube 95 | Tube 97 |
|---|---|---|
| NM extrusion number | 28965 | 28967 |
| Tool temperature (°C) | 480 | 480 |
| Billet temperature (°C) | 630 | 630 |
| Extrusion force, running (tons) | 850 | 740 |
| Extrusion force, maximum (tons) | 1140 | 985 |
| Extrusion constant, running, (tsi) | 17.7 | 15.4 |
| Ram speed (inches/min) | 15 | 15 |
| Extrusion ratio | 15.1 | 15.1 |

Billets, copper-clad
Copper cutoff.

E. Heat Treatment

Both tubes 95 and 97 were given two heat treatments in their copper extrusion jackets--the first at SRL and the second at Atlas Steels, Ltd., Welland, Ontario. The first consisted of 10 minutes in a 735°C salt bath and oil quenched for 5 minutes. Subsequent work at NM indicated air-cooling is preferable to oil-quenching. Therefore, the tubes were given a second heat treatment of 10 minutes in 740°C salt, air-cooled for 6 minutes, and then water-quenched for 2 minutes.

F. Autoclave Test

Tubes 95 and 97 were tested for 4 hours at 345°C in water followed by 4 hours at 400°C in 1500 psi steam. Both tubes exhibited a continuous, hard, black oxide surface.

G. Remarks

This group of 18 tubes resulted in obtaining an acceptable billet design for thin-wall outer tubes for both full-length tubes and VBWR short-length tubes.

H. Current Condition

Tubes 95 and 97 are stored at SRL and are not considered suitable for irradiation. Tube 96 is stored at NM in the as-extruded condition.

17. NM Tube Nos. 100-105

Ref: (1) Progress Reports NMI-7227, 7229, 7230, 7231, 7232, 7233.

(2) NMI-7206, 3/28/61, W.L.Larson, "Evaluation of Zircaloy-4 Clad Unalloyed Uranium Inner Tubes Nos. 103 and 104 Made For Irradiation Testing at Savannah River Plant".

(3) NMI-7207, 12/2/60, W.L.Larson, "Evaluation of Zircaloy-4 Clad Unalloyed Uranium Inner Tube No. 105 Made for Flow Testing at SRP".

As part of the development program to produce unalloyed uranium thin-wall inner tubes for the HWCTR, a group of three experimental (100-102) and three prototype (103-105) tubes were fabricated. This tube, 1.020" OD X 0.180" wall (nominal), is the inner of two concentric tubes designed to replace the thick-wall single fuel tube design. The three experimental tubes were destructively evaluated. Of the three prototypes, one (105) was used for flow tests at SRL with the other two (103,104) irradiated at SRP. Data for the three prototype tubes are presented below.

A. Description

Thin-wall inner tube, 1.020" OD X 0.180" wall (nominal).

Drawing ST-MDX4-3144.

B. Composition

Core: Unalloyed uranium

Cladding: Zircaloy-4 (25 mils)

End seals: Integral-type, zirconium

C. Dimensions

Taken before final bright-etching. (ID should be increased 0.003" and OD decreased by 0.003".)

| | Tube 103 (inches) | Tube 104 (inches) | Tube 105 (inches) |
|---|---|---|---|
| Over uniform core, OD | 1.023 | 1.023 | 1.021 |
| " " " , ID | 0.654 | 0.654 | -- |
| Over end seals, OD | 1.028 | 1.028 | 1.027 |
| " " " , ID | 0.656 | 0.655 | 0.656 |
| Overall length | 118 | 118 | 118 |
| Core, tip-to-tip | 106-1/2 | 106-9/16 | 106-9/16 |

D. Extrusion Conditions

| | Tube 103 | Tube 104 | Tube 105 |
|---|---|---|---|
| NM extrusion number | 29309 | 20310 | 29311 |
| Tool temperature (°C) | 480 | 480 | 480 |
| Billet temperature (°C) | 630 | 630 | 630 |
| Extrusion force, running (tons) | 458 | 440 | 500 |
| Extrusion force, maximum " | 596 | 617 | 678 |
| Extrusion constant, running (tsi) | 16.7 | 16.0 | 18.2 |
| Ram speed (inches/min) | 13 | 13 | 13 |
| Extrusion ratio | 17.6 | 17.6 | 17.6 |
| Billets, copper-clad | | | |
| Copper cutoff | | | |

E. Heat Treatment

Tubes 103 and 104 were beta-treated at Atlas Steels, Ltd., Welland, Ontario, in their copper extrusion jackets. The tubes were rotated at 15 rpm during the heat treating cycle to minimize warpage. The cycle consisted of (1) 10 minutes in 740°C salt; (2) air-cooling for 6 minutes; and (3) quenching in 20°C water for 2 minutes.

No heat treatment was given to tube 105.

F. Autoclave Test

All three tubes were tested for 4 hours at 345°C in water followed by 4 hours at 400°C in 1500 psi steam. The tubes all exhibited a continuous, hard, black oxide surface.

G. Remarks

**None.**

H. Current Condition

Tobe 105 is stored at SRL; it is not suitable for irradiation.

18. NM Tube Nos. 107-112

Ref: (1) Progress Reports NMI-7230, 7232, 7233, 7234.

(2) NMI-7209, 5/2/61, H.F.Sawyer and E.F.Jordan, "Evaluation of the Demonstration Set of Zircaloy-4 Clad Unalloyed Uranium Outer Tubes Nos. 108-112 - Extrusion Nos. 29778 to 29782."

As a follow-up to the 18 experimental thin-wall outer tubes (Item 16), a demonstration set of six full-length tubes was fabricated. The first tube of this set (107) was destructively evaluated and appeared to meet all specifications. Based on this, the remaining five billets were machined, assembled and extruded. Tube 108 was irradiated at SRP and tube 111 was used for flow tests. Data for tubes 108-112 are presented below.

A. Description

Thin-wall tubes, 2.060" OD X 0.180" wall (nominal).

B. Composition

Core: Unalloyed uranium

Cladding: Zircaloy-4 (25 mils)

End seals: Integral-type, zirconium

C. Dimensions

Taken before final bright-etching. ID should be increased 0.003" and OD decreased by 0.003".)

| | Tube Numbers | | | | |
|---|---|---|---|---|---|
| | 108 (in.) | 109 (in.) | 110 (in.) | 111 (in.) | 112 (in.) |
| Over uniform core, OD | 2.059 | 2.061 | 2.059 | 2.057 | 2.060 |
| " " " , ID | 1.695 | 1.694 | 1.696 | 1.694 | 1.693 |
| Over end seals, OD | 2.071 | 2.067 | 2.069 | 2.065 | 2.070 |
| " " " , ID | 1.698 | 1.706 | 1.699 | 1.693 | 1.700 |
| Overall length | 118 | 118 | 118 | 118 | 118 |
| Core, tip-to-tip | 110.4 | 109.7 | 111.1 | 111.4 | 110.8 |

D. Extrusion Conditions

| | Tube Numbers | | | | |
|---|---|---|---|---|---|
| | 108 | 109 | 110 | 111 | 112 |
| NM extrusion number | 29778 | 29779 | 29780 | 29781 | 29782 |
| Tool temperature (°C) | 480 | 480 | 480 | 480 | 480 |
| Billet temperature (°C) | 630 | 630 | 630 | 630 | 630 |
| Extrusion force, running (tons) | 805 | 835 | 725 | 770 | 825 |
| " " , maximum " | 1050 | 1050 | 970 | 980 | 1050 |
| Extrusion constant, running (tsi) | 16.6 | 17.2 | 14.9 | 15.8 | 17.0 |
| Ram speed (inches/min) | 15 | 15 | 15 | 15 | 15 |
| Extrusion ratio | 15.1 | 15.1 | 15.1 | 15.1 | 15.1 |
| Billets, copper-clad | | | | | |
| Copper cutoff | | | | | |

E. Heat Treatment

All five tubes were beta-treated at Atlas Steels, Ltd., Welland, Ontario, in their copper extrusion jackets. The tubes were rotated at 15 rpm during the heat treating cycle. The cycle consisted of (1) 10 minutes in 740 °C salt; (2) air cooling for 6 minutes; and (3) quenching in 20 °C water for 2 minutes.

F. Autoclave Test

The tubes were tested for 4 hours at 345 °C in water followed by 4 hours at 400 °C in 1500 psi steam. All tubes exhibited a continuous, hard, black oxide surface.

G. Remarks

None.

H. Current Condition

Tube 111 is stored at SRL and is not considered suitable for irradiation. Tubes 109, 110 and 112 are stored at NM with only 110 considered suitable for irradiation.

19. NM Tube Nos. 114-115

Ref: (1) Progress Reports NMI-7233, 7234, 7235.

(2) NMI-7213, 4/2/62, W.J.Richmond, "Evaluation of Zircaloy-Clad Uranium Tubes Nos. 114 and 115".

Two prototype, enriched, thin-wall tubes for VBWR were fabricated. Both tubes are suitable for irradiation and are stored at SRL. Data for these tubes are presented below.

A. Description

Thin-wall tubes, 2.060" OD X 0.180" wall (nominal) for the VBWR.

B. Composition

Core: Unalloyed uranium enriched to 3% $^{235}U$.

Cladding: Zircaloy-2 (25 mils)

End seals: Integral-type, zirconium.

C. Dimensions

Taken before final bright-etching. (ID should be increased 0.003" and OD decreased by 0.003".)

| | Tube 114 (inches) | Tube 115 (inches) |
|---|---|---|
| Over uniform core, OD | 2.062 | 2.061 |
| " " " , ID | 1.693 | 1.692 |
| Over end seals, OD | 2.072 | 2.073 |
| " " " , ID | 1.697 | 1.697 |
| Overall length | 50 | 50 |
| Core, tip-to-tip | 44-1/4 | 44-3/32 |

D. Extrusion Conditions

| | Tube 114 | Tube 115 |
|---|---|---|
| NM extrusion number | 30103 | 30104 |
| Tool temperature (°C) | 480 | 480 |
| Billet temperature (°C) | 630 | 630 |
| Extrusion force, running (tons) | 800 | 770 |
| " " , maximum (tons) | 1000 | 1005 |
| Extrusion constant, running (tsi) | 17.3 | 16.7 |
| Ram speed (inches/min) | 15 | 15 |
| Extrusion ratio | 15.1 | 15.1 |

Billets copper-clad
Copper cutoff

E. Heat Treatment

Both tubes were beta treated in their copper extrusion jackets and consisted of 10 minutes in 740 °C salt followed by air cooling.

F. Autoclave Test

The tubes were tested for 4 hours at 345 °C in water followed by 4 hours at 400 °C in 1500 psi steam. Both tubes exhibited a continuous, hard, black oxide surface.

G. Remarks

None.

H. Current Condition

Both tubes are stored at SRL and are considered suitable for irradiation.

20. NM Tube Nos. 116-121

Ref: (1) Progress Reports NMI-7234, 7235, 7236.

(2) NMI-7210, 8/11/61, W.L.Larson, "Evaluation of the Demonstration Set of Zircaloy-4-Clad Unalloyed Uranium Inner Tubes Nos. 116-121, Extrusion Nos. 30795 to 30800."

This group of six thin-wall inner tubes with unalloyed uranium cores and of identical design were made to demonstrate the reproducibility of the fabrication process. One of the tubes (121) was processed as a flow test tube and was not heat treated. The other five were beta-treated and processed as candidates for irradiation testing. Two of these tubes (117, 119) were irradiated at SRP. Data for the tubes are presented below.

A. Description

Thin-wall inner tubes, 1.020" OD X 0.180" wall (nominal).

B. Composition

Core: Unalloyed uranium

Cladding: Zircaloy-4 (25 mils)

End seals: Integral-type, zirconium.

C. Dimensions

Taken before final bright-etching. (ID should be increased 0.003" and OD decreased by 0.003".)

| | Tube Numbers | | | | | |
|---|---|---|---|---|---|---|
| | 116 (in.) | 117 (in.) | 118 (in.) | 119 (in.) | 120 (in.) | 121 (in.) |
| Over uniform core, OD | 1.026 | 1.024 | 1.024 | 1.022 | 1.023 | 1.020 |
| " " " , ID | 0.654 | 0.653 | 0.654 | 0.656 | 0.654 | 0.651 |
| Over end seals, OD | 1.032 | 1.031 | 1.029 | 1.027 | 1.029 | 1.029 |
| " " " , ID | 0.655 | 0.654 | 0.654 | 0.655 | 0.654 | 0.655 |
| Overall length | 118 | 118 | 118 | 118 | 118 | 118 |
| Core, tip-to-tip | 108.9 | 109.4 | 109.5 | 110.3 | 110.9 | 109.7 |

D. Extrusion Conditions

| | Tube Numbers | | | | | |
|---|---|---|---|---|---|---|
| | 116 | 117 | 118 | 119 | 120 | 121 |
| NM extrusion number | 20795 | 30796 | 30797 | 30798 | 30799 | 30800 |
| Tool temperature (°C) | 480 | 480 | 480 | 480 | 480 | 480 |
| Billet temperature (°C) | 630 | 630 | 630 | 630 | 630 | 630 |
| Extrusion force, running (tons) | 596 | 535 | 435 | 445 | 475 | 510 |
| " " , maximum (tons) | 767 | 725 | 587 | 623 | 689 | 701 |
| Extrusion constant, running(tsi) | 21.8 | 19.6 | 15.9 | 16.2 | 17.4 | 18.6 |
| Ram speed (inches/min) | 13 | 13 | 13 | 13 | 13 | 13 |
| Extrusion ratio | 17.6 | 17.6 | 17.6 | 17.6 | 17.6 | 17.6 |

Billets copper-clad
Copper cutoff

E. Heat Treatment

Tube 121 was not treated.

Tubes 116 through 120 were beta-treated at Atlas Steels, Ltd., Welland, Ontario. The cycle was as follows: (1) 10 minutes in 730 °C salt; (2) 6 minutes air cooling; and (3) water quenching (20 °C) for 2 minutes. The tubes were rotated at 15 rpm during heat treatment in their copper extrusion jackets.

F. Autoclave Test

Tubes 116, 118 and 120 were not tested.

Tubes 117, 119 and 121 were tested for 4 hours at 345 °C in water followed by 4 hours at 400 °C in 1500 psi steam. The tubes exhibited a continuous, hard, black oxide surface.

G. Remarks

**Tubes 120 and 121 were used for flow tests at SRL.**

H. Current Condition

Tubes 116 and 118 are stored at NM and tubes 120 and 121 are stored at SRL. The first two tubes (116, 118) have been etched but not autoclaved and may be candidates for irradiation.

21. NM Tube Nos. 122-124

Ref: Progress Reports NMI-7236, 7237, 7238, 7240.

A group of three experimental tubes was fabricated to improve the quality of unalloyed uranium thin-wall outer tubes. Evaluation of two of these tubes (122,123) showed that more extensive alpha working of the billet core stock results in more uniform cladding and smoother interface on the extruded tube. This was subsequently confirmed by extrusion of a third tube (124). No detailed dimensional data on evaluation of these tubes were reported.

22. NM Tube Nos. 125-127

Ref: (1) Progress Reports NMI-7240, 7241, 7242.

(2) NMI-7214, 8/24/62, W.J.Richmond, "Evaluation of Zircaloy-Clad Unalloyed Uranium Outer Tubes Nos. 125, 126 and 127.

This demonstration set of three unalloyed uranium thin-wall outer tubes were fabricated to evaluate the process for producing the outer tubes for the initial loading of the HWCTR. Data for these tubes are presented below.

A. Description

Thin-wall tubes, 2.060" OD X 0.180" wall (nominal) for the HWCTR.

B. Composition

Core: Unalloyed uranium

Cladding: Nickel-free Zircaloy-2 (25 mils)

End Seals: Integral-type, zirconium

C. Dimensions

| | Tube 125 (inches) | Tube 126 (inches) | Tube 127 (inches) |
|---|---|---|---|
| Over uniform core, OD | 2.056 | 2.055 | 2.055 |
| " " " , ID | 1.697 | 1.696 | 1.695 |
| Over end seals, OD | 2,062 | 2.062 | 2.062 |
| " " " , ID | 1.699 | 1.698 | 1.700 |
| Overall length | 118.0 | 118.0 | 118.0 |
| Core, tip-to-tip | 110.6 | 109.6 | 109.5 |

D. Extrusion Conditions

| | Tube 125 | Tube 126 | Tube 127 |
|---|---|---|---|
| NM extrusion number | 32001 | 32002 | 32003 |
| Tool temperature (°C) | 370 | 370 | 370 |
| Billet temperature (°C) | 630 | 630 | 630 |
| Extrusion force, running (tons) | 790 | 780 | 780 |
| " " , maximum (tons) | 1000 | 950 | 970 |
| Extrusion constant, running (tsi) | 16.4 | 16.1 | 16.1 |
| Ram speed (inches/min) | 15 | 15 | 15 |
| Extrusion ratio | 15.1 | 15.1 | 15.1 |
| Billets copper-clad | | | |
| Copper cutoff | | | |

E. Heat Treatment

The tubes were beta-treated in their copper extrusion jackets at Atlas Steels, Ltd. Each tube was immersed for 10 minutes in 740°C salt, air-cooled for 6 minutes, then water quenched while being rotated at 15 rpm.

F. Autoclave Test

All of the tubes were tested for 4 hours at 345 °C in water followed by 4 hours at 400 °C in 1500 psi steam. Each of the three tubes exhibited a continuous, hard, black oxide surface.

G. Remarks

Tubes 126 and 127 meet all specifications for irradiation candidates. Tube 125 was satisfactory in all respects except overall bow which was 5/32 inch (1/8" maximum specified). This tube was later straightened to a bow of 1/16".

H. Current Condition

All three tubes are stored at NM and are suitable for irradiation.

23. NM Tube Nos. 128-129, 136

Ref: (1) Progress Reports NMI-7239, 7240, 7241, 7242, 7243, 7244, 7247.

(2) NMI-7215 DE, 7/16/62, E.F.Jordan, "Evaluation of Restraint Tubes 128, 129 and 136".

A group of three thin-wall inner tubes having unalloyed uranium cores was fabricated to evaluate the effect of cladding restraint on fuel swelling during irradiation. Tubes 128 and 136 are identical in design, with 60 mils cladding as compared with the nominal 25 mils normally used. Tube 129 has 40 mils outside and 25 mils inside cladding. Tube 136 was fabricated as a substitute for 128 which had a striation on the outside cladding making it unsuitable for irradiation. Data for the three tubes are presented below.

A. Description

Thin-wall restraint inner tubes.

Type D: (128,136), 1.020" OD X 0.520" ID, 0.130" core, 0.060" outer and 0.060" inner clad.

Type E: (129), 1.020" OD X 0.630" ID, 0.130" core, 0.040" outer and 0.025" inner clad.

B. Composition

Core: Unalloyed uranium

Cladding: Nickel-free Zircaloy-2 (thickness as above)

End seals: Integral-type, zirconium

C. Dimensions

| | Tube 128 (inches) | Tube 136 (inches) | Tube 129 (inches) |
|---|---|---|---|
| Over uniform core, OD | 1.015 | 1.016 | 1.019 |
| " " " , ID | 0.523 | 0.520 | 0.630 |
| Over end seals, OD | 1.030 | 1.020 | 1.028 |
| " " " , ID | 0.522 | 0.520 | 0.629 |
| Overall length | 118 | 118 | 118 |
| Core, tip-to-tip | 105.2 | 107.1 | 108.0 |

D. Extrusion Conditions

| | Tube 128 | Tube 136 | Tube 129 |
|---|---|---|---|
| NM extrusion number | 32039 | 33158 | 32040 |
| Tool temperature (°C) | 480 | 370 | 480 |
| Billet temperature (°C) | 630 | 630 | 630 |
| Extrusion force, running (tons) | 519 | 392 | 551 |
| " " , maximum (tons) | 689 | 519 | 731 |
| Extrusion constant, running (tsi) | 20.2 | 15.2 | 20.4 |
| Ram speed (inches/min) | 13 | 13 | 13 |
| Extrusion ratio | 14.3 | 14.3 | 16.8 |

Billets copper-clad
Copper cutoff

E. Heat Treatment

Tubes 128 and 129 were heat treated at Atlas Steels, Ltd. with tube 136 done at Watertown Arsenal. Each tube was beta treated in its copper extrusion jacket while being rotated at 17½ rpm. Treatment consisted of immersion in a 730°C salt bath for 10 minutes, air-cooled for 6 minutes, and water-quenched for 2 minutes.

F. Autoclave Test

Tube 129 was tested for 4 hours at 345°C in water followed by 4 hours at 400°C in 1500 psi steam. Tubes 128 and 136 underwent a similar test but were held for 32 hours in steam. All tubes exhibited the black oxide film associated with Zircaloy having good aqueous corrosion resistance, except for tube 128 which exhibited localized white oxide in the heavily-scored section of the outside cladding.

G. Remarks

None.

H. Current Condition

Tube 128 is stored at NM and is not considered suitable for irradiation. Tubes 129 and 136 are stored at SRL and are both suitable for irradiation.

24. NM Tube Nos. 130-133

Ref: (1) Progress Reports NMI-7239, 7240, 7241, 7242, 7243, 7244, 7247.

(2) NMI-7215 BC, 6/20/62, E.F.Jordan, "Evaluation of Restraint Tubes 130 and 131".

(3) NMI-7215-A, 6/14/62, E.F.Jordan, "Evaluation of Restraint Tubes 132 and 133".

A group of four thin-wall outer tubes having unalloyed uranium cores were fabricated to evaluate the effect of cladding restraint on fuel swelling during irradiation. Tubes 132 and 133 had 60 mils outer and inner clad; tube 130, 25 mil outer and 40 mil inner; tube 131, 40 mil outer and 25 mil inner. Tube 132 was not considered an irradiation candidate because of white oxide formation during autoclaving; tube 133 was irradiated in HWCTR. Data for the four tubes are presented below.

A. Description

Thin-wall restraint outer tubes.

Type A: (132,133), 2.060" OD X 1.560" ID, 0.130" core, 0.060" outer and 0.060" inner clad.

Type B: (130), 2,060" OD X 1.670" ID, 0.130" core, 0.025" outer and 0.040" inner clad.

Type C: (131), 2.060" OD X 1.670" ID, 0.130" core, 0.040" outer and 0.025" inner clad.

B. Composition

Core: Unalloyed uranium

Cladding: Nickel-free Zircaloy-2 (thickness as above)

End Seals: Integral type, zirconium.

C. Dimensions

| | Tube 132 (inches) | Tube 133 (Inches) | Tube 130 (inches) | Tube 131 (inches) |
|---|---|---|---|---|
| Over uniform core, OD | 2.068 | 2.070 | 2.052 | 2.055 |
| " " " , ID | 1.567 | 1.568 | 1.667 | 1.671 |
| Over end seals, OD | 2.072 | 2.075 | 2.061 | 2.062 |
| " " " , ID | 1.566 | 1.567 | 1.671 | 1.670 |
| Overall length | 118 | 118 | 118 | 118 |
| Core, tip-to-tip | 108.3 | 107.8 | 109.2 | 109.8 |

D. Extrusion Conditions

Tubes 132 and 133 were extruded at American Brass Co.

| | Tube 132 | Tube 133 | Tube 130 | Tube 131 |
|---|---|---|---|---|
| NM extrusion number | 32995 | 32996 | 32345 | 32346 |
| Tool temperature (°C) | 480 | 480 | 370-480(1) | 370-480(1) |
| Billet temperature (°C) | 630 | 630 | 630 | 630 |
| Extrusion force, running (tons) | 1200 | 1160 | 765 | 755 |
| " " , maximum (tons) | 1400 | -- | 935 | 890 |
| Extrusion constant, running (tsi) | 18.6 | 18.0 | 16.1 | 15.9 |
| Ram speed (inches/min) | 25 | 25 | 15 | 15 |
| Extrusion ratio | 14.3 | 14.3 | 14.2 | 14.2 |

Billet copper-clad
Copper cutoff

(1) Die and liner at 370 °C; mandrelland cutoff at 480 °C.

E. Heat Treatment

All four tubes were beta treated in their copper extrusion jackets at Atlas Steels, Ltd. The tubes were immersed in 730 °C salt for 10 minutes, air-cooled for 6 minutes, and water-quenched for 2 minutes. Tubes 130 and 131 were rotated at 15 rpm and tubes 132 and 133 at 17½ rpm during heat treatment.

F. Autoclave Test

The tubes were tested for 4 hours at 345 °C in water followed by 4 hours (130, 131) or 32 hours (132, 133) at 400 °C in 1500 psi steam. Tube 132 exhibited white oxide, indicative of excessive corrosion, on both the outside and inside surfaces between 18 and 36 inches from the rear of the tube. The remaining three tubes all exhibited a continuous black oxide surface film associated with good corrosion resistance in water.

G. Remarks

None.

H. Current Condition

Tubes 130 and 131 are stored at SRL and are considered suitable for irradiation. Tube,132, stored at NM, is not an irradiation candidate.

25. NM Tube Nos. 134-135, 141-142

Ref: (1) Progress Reports NMI-7241, 7242, 7243, 7244, 7247, 7249, 7250, 7251, 7252.

(2) NMI-7217, 6/29/62, W.J.Richmond, "Evaluation of Zircaloy-Clad U-0.3 w/o Al-0.5 w/o Si Tube No. 135".

(3) NMI-7219, 1/15/63, W.J.Richmond, "Evaluation of Zircaloy-Clad U-1 w/o Si Tube No. 141".

To obtain thin-wall outer tubes containing cores of different uranium alloys that might be superior to unalloyed uranium in resistance to deformation during irradiation, a group of four tubes with three different core alloys were fabricated. Two tubes (134, 141) contained cores of U-1 w/o Si with tube 134 being scrapped following stalling during extrusion and tube 135 being processed as an irradiation candidate. Tube 135 contained a core of U-0.3 w/o Al-0.5 w/o Si and tube 142 a core of U-1.5 w/o Mo, with 135 being processed as an irradiation candidate and 142 processed only through extrusion. Data for the three types of tubes are presented below.

A. Description

Thin-wall outer tubes, 2.060" OD X 0.180" wall (nominal).

B. Composition

Core: 134 and 141 - U-1 w/o Si.
135 - U-0.3 w/o Al-0.5 w/o Si
142 - U-1.5 w/o Mo

Cladding: Nickel-free Zircaloy-2 (25 mils)

End seals: Integral-type, nickel-free Zircaloy-2

C. Dimensions

| | Tube 135 (inches) | Tube 141 (inches) | Tube 142 (inches) |
|---|---|---|---|
| Over uniform core, OD | 2.065 | 2.054 | -- |
| " " " , ID | 1.698 | 1.700 | -- |
| Over end seals, OD | 2.076 | 2.064 | -- |
| " " " , ID | 1.706 | 1.706 | -- |
| Overall length | 118 | 118 | 118 |
| Core, tip-to-tip | 112.1 | 115.1 | (113 spec.) |

D. Extrusion Conditions

This group of tubes was extruded at American Brass Co.

| | Tube 135 | Tube 141 | Tube 142 |
|---|---|---|---|
| NM extrusion number | 32998 | 35897 | ---- |
| Tool temperature (°C) | 430-480(1) | 430-480 | 430-480 |
| Billet temperature (°C) | 650 | 650 | 630 |
| Extrusion force, running (tons) | 1304 | 1301 | 1134 |
| " " , maximum (tons) | 1672 | 1321 | 1374 |
| Extrusion constant, running (tsi) | 20.3 | 20.2 | 17.6 |
| Ram speed (inches/min) | 25 | 25 | 25 |
| Extrusion ratio | 18.3 | 18.8 | 18.8 |

Billets copper-clad

Copper cutoff

(1) Linner at 430°C; die, mandrel and cutoff at 480°C.

E. Heat Treatment

Tube 135 and 141 were beta treated in their copper extrusion jackets at Watertown Arsenal. The tubes were immersed in 740°C salt for 10 minutes, air-cooled for 6 minutes, and water-quenched for 2 minutes. They were both rotated at 17½ rpm during treatment to minimize warpage. Tube 142 was not heat treated.

F. Autoclave Test

The tubes were tested for 4 hours at 345°C in water followed by 32 hours in 1500 psi steam. Both tubes exhibited a continuous, black surface film after the test. Tube 142 was not tested.

G. Remarks

None.

H. Current Condition

Tubes 135 and 142 are stored at SRL and are considered suitable for irradiation. Tube 142 is stored at NM in the as-extruded condition.

26. NM Tubes Nos. 137, 143-147

Ref: (1) Progress Reports NMI-7248 and 7249.

(2) NMI-7220-1, 3/15/63, A.B.Bremer, "Evaluation of Five Inner Tubes of Zircaloy-Clad Enriched Uranium Tubes Nos. 143-147".

This group of thin-wall inner tubes consisted of one prototype with a natural uranium core and five enriched uranium (2.1% $^{235}U$) tubes for irradiation tests in HWCTR. The prototype (137) was extruded to provide information on billet design and also to provide nonbond standards for ultrasonic testing. All five of the enriched tubes (143-147) met the specifications for irradiation testing. Data for these tubes are presented below.

A. Description

Thin-wall inner tubes, 1.020" OD X 0.180" wall (nominal).

B. Composition

Core: Tube 137 - Unalloyed U (natural)
Tubes 143-147 - Unalloyed U enriched to 2.1 % $^{235}U$.

Cladding: Nickel-free Zircaloy-2 (25 mils)

End seals: Integral-type, zirconium

C. Dimensions

| | Tube 143 (inches) | Tube 144 (inches) | Tube 145 (inches) | Tube 146 (inches) | Tube 147 (inches) |
|---|---|---|---|---|---|
| Over uniform core, OD | 1.021 | 1.020 | 1.020 | 1.021 | 1.021 |
| " " " , ID | 0.660 | 0.658 | 0.659 | 0.659 | 0.660 |
| Over end seals, OD | - | - | - | - | - |
| " " " , ID | - | - | - | - | - |
| Overall length | 118 | 118 | 118 | 118 | 118 |
| Core, tip-to-tip | 109.4 | 109.0 | 109.0 | 108.7 | 108.9 |

D. Extrusion Conditions

| | Tube Numbers | | | | |
|---|---|---|---|---|---|
| | 143 | 144 | 145 | 146 | 147 |
| NM extrusion number | 35929 | 35930 | 35931 | 35932 | 35933 |
| Tool temperature (°C) | 370 | 370 | 370 | 370 | 370 |
| Billet temperature (°C) | 630 | 630 | 630 | 630 | 630 |
| Extrusion force, running (tons) | 425 | 500 | 450 | 460 | 490 |
| " " " , maximum (tons) | 615 | 680 | 590 | 605 | 660 |
| Extrusion constant, running (tsi) | 15.5 | 18.2 | 16.4 | 16.8 | 17.9 |
| Ram speed (inches/min) | 13-15 | 13-15 | 13-15 | 13-15 | 13-15 |
| Extrusion ratio | 17.7 | 17.7 | 17.7 | 17.7 | 17.7 |
| Billet copper-clad | | | | | |
| Copper cutoff | | | | | |

E. Heat Treatment

Tubes 143 and 145-147 were beta treated at SRL in their copper extrusion jackets. The tubes were immersed in a 740 °C salt bath for 10 minutes and oil-quenched for 20 minutes. Tube 144 was beta treated at Watertown Arsenal in a 740 °C salt bath for 10 minutes, air-cooled for 6 minutes and quenched in water for 2 minutes while being rotated at 15 rpm. (The other tubes were not rotated.)

F. Autoclave Test

The tubes were tested for 4 hours at 345 °C in water followed by 32 hours at 400 °C in 1500 psi steam. All tubes exhibited a continuous, lustrous, black surface film.

G. Remarks

Nonbonds on the prototype tube (137) were obtained on the outside core-cladding interface by interposing either mica or uranium oxide. To accommodate these nonbond materials in the billet, two $\frac{1}{2}$-inch wide recesses 0.060" deep for the mica and 0.015" deep for the uranium oxide, were machined in the uranium core. A strip of outgassed mica 0.5-inch wide X 0.0025-inch thick was wrapped 8.7 turns into the 0.060" recess to produce a 0.004" thick X 7.5" long layer in the extruded tube. The uranium oxide was produced by torch-oxidizing the surface of the 0.015" recess.

H. Current Condition

The five enriched tubes are stored at SRL and are all suitable for irradiation.

27. NM Tubes Nos 138-140

Ref: Progress Report NMI-7249.

Three thin-wall outer tubes (138-140) were extruded to qualify a simplified process for preparing fine-grain unalloyed uranium cores. The new process consisted of beta treatment followed by a single extrusion at low reduction as compareed to the low-yield process of repreated alpha extrusions with intermediate upsets, (known as Process B). Data for these tubes are presented below.

A. Description

Thin-wall outer tubes, 2.060" OD X 0.180" wall (nominal).

B. Composition

Core: Unalloyed uranium

Cladding: Nickel-free Zircaloy-2 (25 mils)

End seals: Integral-type, zirconium

C. Dimensions

Not reported.

D. Extrusion Conditions

| | Tube 138 | Tube 139 | Tube 140 |
|---|---|---|---|
| NM extrusion number | 35820 | 35821 | 35822 |
| Tool temperature (°C) | 370 | 370 | 370 |
| Billet temperature (°C) | 630 | 630 | 630 |
| Extrusion force, running (tons) | 810 | 830 | 855 |
| Extrusion force, maximum (tons) | 970 | 1015 | 1080 |
| Extrusion constant, running (tsi) | 16.7 | 17.1 | 17.6 |
| Ram speed (inches/min) | 15 | 15 | 15 |
| Extrusion ratio | 15.0 | 15.0 | 15.0 |

Billets copper-clad
Copper cutoff

E. Heat Treatment

None.

F. Autoclave Test

None

G. Remarks

All three tubes were destructively examined. The simplified core preparation process resulted in tubes having core-cladding interfaces as smooth as in tubes with cores prepared by the alpha extrusion-intermediate upset process.

28. NM Tubes Nos. 148-149

Ref: NMI-7220-2, 3/15/63, A.B.Bremer, "Evaluation of Two Outer Tubes of Zircaloy-Clad Enriched Unalloyed Uranium Tube Nos. 148 and 149."

Two thin-wall outer tubes with unalloyed uranium enriched to 2.1% $^{235}U$ were fabricated for irradiation tests which were done in the HWCTR. Data for these two tubes are presented below.

A. Description

Thin-wall outer tubes, 2.060" OD X 0.180" wall (nominal).

B. Composition

Core: Unalloyed U enriched to 2.1% $^{235}U$.

Cladding: Nickel-free Zircaloy-2 (25 mils)

End seals: Integral-type, zirconium

C. Dimensions

| | Tube 148 (inches) | Tube 149 (inches) |
|---|---|---|
| Over Uniform core, OD | 2.057 | 2.060 |
| " " " , ID | 1.699 | 1.699 |
| Over end seals, OD | - | - |
| " " " , ID | - | - |
| Overall length | 118 | 118 |
| Core, tip-to-tip | 109.8 | 108.8 |

D. Extrusion Conditions

| | Tube 148 | Tube 149 |
|---|---|---|
| NM extrusion number | 36308 | 36309 |
| Tool temperature (°C) | 370 | 370 |
| Billet temperature (°C) | 630 | 630 |
| Extrusion force, running (tons) | 738 | 730 |
| " " , maximum (tons) | 895 | 870 |
| Extrusion constant, running (tsi) | 15.2 | 15.0 |
| Ram speed (inches/min) | 13-15 | 13-15 |
| Extrusion ratio | 15.0 | 15.0 |

Billets copper-clad
Copper cutoff

E. Heat Treatment

Both tubes were beta treated at SRL in their copper extrusion jackets. Treatment consisted of immersion in a 740 °C salt bath for 10 minutes followed by quenching in oil for 20 minutes.

F. Autoclave Test

The tubes were tested for 4 hours at 345 °C in water followed by 32 hours at 400 °C in 1500 psi steam. Both tubes exhibited a continuous, lustrous, black surface film.

G. Remarks

None.

29. NM Tubes Nos. 150-155 and 157-158

Ref: (1) Progress Reports NMI-7256, 7257, 7258, 7259, 7260.

To further the development of new fuel compositions, short tubular elements were prepared from long extruded tubes. The short elements provided means for irradiating a wider range of compositions and/or heat treatment in a minimum of reactor positions, as well as expediting postirradiation examination. These short tubes were 1.700" OD X 0.230" wall X 11¼" long (nominal) with brazed end seals at both ends. A total of 24 short elements consisting of four variations of heat treatment and composition were sent to SRL as irradiation candidates. Fifteen of these tubes, five from each of tubes 153, 154 and 158, were irradiated in HWCTR. Data for this group of tubes is presented below.

A. Description

Short HWCTR tubular elements, 1.700" OD X 0.230" wall X 11¼" long (nominal).

B. Composition

Core: 150 and 151 - Unalloyed uranium
152-154 - U-350 ppm Fe-900 ppm Al
155 - U-350 ppm Fe-900 ppm Al-500 ppm Si-1000 ppm Mo
157 and 158 - U-350 ppm Fe-900 ppm Al-300 ppm Si

Cladding: Zircaloy-2 (22 mils)

End seals: Brazed type, Zircaloy-2

C. Dimensions

The following dimensions are typical of the short tubes which were irradiated in HWCTR.

| | Tube Numbers | | |
|---|---|---|---|
| | 153-4 (inches) | 154-4 (inches) | 158-4 (inches) |
| Over uniform core, OD | 1.690 | 1.690 | 1.689 |
| " " " , ID | 1.234 | 1.234 | 1.234 |
| Over end seals, OD | 1.701 | 1.700 | 1.701 |
| " " " , ID | 1.231 | 1.233 | 1.234 |
| Overall length | 11.294 | 11.300 | 11.263 |
| Core length | 10.721 | 10.750 | 10.713 |
| End seal length, front | 0.275 | 0.275 | 0.275 |
| " " " , rear | 0.275 | 0.275 | 0.275 |
| Clad thickness, outside | 0.022 | 0.021 | 0.022 |
| " " , inside | 0.022 | 0.022 | 0 023 |

D. Extrusion Conditions

| | Tube Numbers | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 150 | 151 | 152 | 153 | 154 | 155 | 157 | 158 |
| NM extrusion number | 36692 | 36693 | 36823 | 36824 | 36825 | 36826 | 37108 | 37109 |
| Tool temp. (°C) | ---------- | ---------- | ---------- | 370 | ---------- | ---------- | ---------- | ---------- |
| Billet temp. (°C) | ---------- | ---------- | ---------- | 595 | ---------- | ---------- | ---------- | ---------- |
| Extrusion force, running (tons) | 750 | 750 | 950 | 910 | 950 | 1130 | 1000 | 960 |
| Extrusion force, maximum (tons) | 750 | 780 | 1000 | 990 | 980 | 1180 | 1040 | 990 |
| Extrusion constant, running (tsi) | 15.5 | 15.5 | 19.7 | 19.0 | 19.7 | 23.3 | 20.7 | 19.9 |
| Ram speed (in./min.) | 30 | 30 | 42 | 42 | 42 | 42 | 42 | 42 |
| Extrusion ratio | ---------- | ---------- | ---------- | 14.7 | ---------- | ---------- | ---------- | ---------- |

Billets copper-clad
Copper cutoff

E. Heat Treatment

The core stock for the unalloyed U tubes (150,151) was triple beta treated followed by a series of extrusions and intermediate upsets to obtain the desired grain size for extrusion. Preparation for the cores of tubes 152, 153, 155, 157 and 158 differed in that they were beta treated-air cooled and beta treated-oil quenched in place of a triple beta treatment. For tube 154, the core was gamma treated by being held at 800 to 850°C for 2 hours and furnace cooled.

Following brazing of the end caps, the completed short tubes made from long tubes 151, 153, 154 and 158 were beta treated at 730 °C for 15 minutes followed by an oil quench. The alloyed tubes (from 153, 154 and 158) were then stress-relieved at 500 °C for 60 minutes followed by air cooling.

F. Autoclave Test

All 24 tubes shipped to SRL were tested at 345 °C in water for 4 hours followed by 32 hours at 400 °C in 1500 psi steam. The satisfactory quality of the Zircaloy surfaces was indicated by the lustrous, black oxide film that was formed. Exception to this was on the tube ends where the film ranged from dull black to light gray on the weld metal only and was not considered detrimental.

G. Preparation of End Seals

Tube sections of 12½" length were cut and faced square, the copper removed by pickling and the ends recessed to a depth of about 0.7". The recessing was effected by chemical milling over a period of 12 to 14 hours. Next, the tube end was cleaned, etched and a ½" long Zircaloy-2 end plug inserted with a ring of braze alloy (Zircaloy-2-5 w/o Be) placed on top of it. The assembled end closure was placed in a vacuum induction furnace. Induction heating to 60 °C above the braze alloy melting point (940 °C) was done in a vacuum of less than 0.5 micron. After a hold of 1½ minutes at temperature, the furnace was backfilled with dry argon and held at temperature for an additional 3 minutes and cooled. The brazed end was machined to the finished length of 0.275". Following heat treatment of the tube, the ends were cleaned and TIG-welded in an argon atmosphere.

H. Remarks

None.

I. Current Condition

The six short tubes from 151 and tubes 153-5, 154-3, and 158-2 are stored at SRL with only the 151 and 158-2 tubes being suitable for irradiation. Short lengths of tube stock from 151, 153, 154, 155, 157 and 158 are stored at NM.

30. NM Tubes Nos. 156, 159, 163-164

(1) Progress Reports NMI-7258, 7259

(2) NMI-7262, 9/4/64, S.Isserow and others, "Development of Fabrication Processes for Concentric Driver Tubes for HWCTR".

These four tubes were the prototype outers of a concentric two-tube design for the HWCTR drivers to permit operation at higher power levels. Two of the Zr-6.5 w/o natural U tubes (159,163) were destructively evaluated with tube 164 being used for flow tests at SRL. This two-tube driver tube design was superseded by a single tube driver design (Item 32) for economic reasons. Data for tubes 159 and 163 are presented below.

A. Description

Outer HWCTR driver tube, 2.700" OD X 0.135" wall (nominal).

B. Composition

Core: Zircaloy-2, 6.5 w/o U (natural)

Cladding: Zircaloy-2 (15 mils)

End seals: Integral-type, Zircaloy-2

C. Dimensions

(As-extruded condition).

| | Tube 159 (inches) | Tube 163 (inches) |
|---|---|---|
| Outside diameter, average | 2.700 | 2.703 |
| Inside diameter, average | 2.424 | 2.427 |
| Outside cladding, average | 0.016 | 0.016 |
| Core, average | 0.106 | 0.105 |
| Inside cladding, average | 0.016 | 0.017 |
| Overall length, nominal | 119.0 | 119.0 |
| Maximum core, tip-to-tip, nominal | 113.0 | 113.0 |

D. Extrusion Conditions

| | Tube 159 | Tube 163 |
|---|---|---|
| Tool temperature (°C) | 370-430(1) | 370-430 |
| Billet temperature (°C) | 755 | 750 |
| Extrusion force, running (tons) | 1050-1150 | 1050-1150 |
| Extrusion force, maximum (tons) | 1310 | 1270 |
| Extrusion constant, running (tsi) | 19.1-20.9 | 19.1-20.9 |
| Ram speed (inches/min) | 33 | 36 |
| Extrusion ratio | 16.2 | 16.2 |
| Billets copper-clad | | |
| Copper cutoff | | |

(1) Liner at 430°C; die, mandrel and cutoff at 370°C.

E. Heat Treatment

None.

F. Autoclave Test

None.

G. Remarks

None

H. Current Condition

Tube 164 is stored at SRL.

31. NM Tubes Nos. 160-162, 165-166

Ref: (1) Progress Reports NMI-7258, 7259.

(2) NMI-7262, 9/4/64, S.Isserow and others, "Development of Fabrication Processes for Concentric Tubes for HWCTR".

Five inner tubes with four shallow ribs were fabricated as prototypes for the concentric two-tube design for HWCTR drivers. The first three (160-162) used rib stock inserted in the billet as Zircaloy strips. Since only the first of these was satisfactory, two additional inner tubes (165,166) were fabricated with the rib stock machined as part of the outer Zircaloy sleeve of the billet. Both of these latter tubes were satisfactory. Tube 160 was used by Dresser Products, Inc., Great Barrington, Mass., to demonstrate that 0.060" thick full-height (0.300") ribs could be satisfactorily electron-beam welded along the full 117.5" length of shallow-ribbed inner tubes. Work on the concentric two-tube design was superseded by a single tube driver design (Item 32) for economic reasons. Data for tubes 160 and 166 are presented below.

A. Description

Inner HWCTR driver tube, 1.720" OD between ribs, 1.800" OD across shallow ribs, 0.160" wall, and 2.390" OD rib circle with full-height ribs (nominal).

B. Composition

Core: Zircaloy-2, 6.5 w/o U (natural)

Cladding: Zircaloy-2 (15 mils)

End seals: Integral-type, Zircaloy-2.

C. Dimensions

(As-extruded condition)

| | Tube 160 (inches) | Tube 166[1] (inches) |
|---|---|---|
| OD across shallow ribs, average | 1.811 | 1.802 |
| OD between ribs, average | 1.725 | 1.720 |
| ID between ribs, average | 1.395 | -- |
| Outside cladding, average | 0.017 | -- |
| Core, average | 0.132 | -- |
| Inside cladding, average | 0.017 | -- |
| Overall length, nominal | 117.5 | 117.5 |
| Maximum core, tip-to-tip, nominal | 113.0 | 113.0 |
| Welded rib width | 0.060 | -- |
| OD across welded ribs, average | 2.432[2] | -- |

(1) Tube 166 not dimensionally evaluated.
(2) Rib stock used for test work was 0.300" wide (0.285" width would be used for tubes intended for flow tests or irradiation candidates.

D. Extrusion Conditions

| | Tube 160 | Tube 166 |
|---|---|---|
| Tool temperature (°C) | 370-430[1] | 370-430 |
| Billet temperature (°C) | 750 | 750 |
| Extrusion force, running (tons) | 860-1010 | 810-910 |
| Extrusion force, maximum (tons) | 1050 | 1040 |
| Extrusion constant, running (tsi) | 16.4-19.2 | 15.4-17.4 |
| Ram speed (inches/min) | 30 | 33 |
| Extrusion ratio | 16.9 | 16.9 |

Billets copper-clad
Copper cutoff

(1) Liner at 430°C; die, mandrel and cutoff at 370°C.

E. Heat Treatment

None.

F. Autoclave Test

None

G. Remarks

None

H. Current Condition

Tubes 162, 165 and 166 are stored at NM.

32. NM Tubes Nos. 167-169

Ref: NMI-7263, 11/30/64, J. Siergiej and others, "Development of Fabrication Process for Driver Tubes for the HWCTR".

Three prototype single-tube drivers for HWCTR were fabricated using Zircaloy-2, 11.1 w/o uranium cores to establish the process for manufacture of a set of 28 tubes for the M-3 fuel set. The design of these tubes is externally identical to the outer tube of the two-tube driver element previously described (Item 30). The uranium in the core alloy was increased from 6.5 w/o to 11.1 w/o, placing in this tube all the uranium (oralloy, 93% $^{235}U$, in case of the M-3 fuel set) that was originally to be distributed between the two tubes of the earlier design. All three prototypes were destructively evaluated, proving the process to be satisfactory. Data for tubes 167 and 168 are presented below.

A. Description

Single-tube design HWCTR driver tube, 2.700" OD, 0.135" wall (nominal).

B. Composition

Core: Zircaloy-2, 11.1 w/o U (natural).

Cladding: Zircaloy-2 (15 mils).

End seals: Integral-type, Zircaloy-2.

C. Dimensions

(As-pickled condition)

| | Tube 167 (inches) | Tube 168 (inches) |
|---|---|---|
| OD, average | 2.703 | 2.704 |
| ID, average | 2.426 | 2.428 |
| Outside cladding, average | 0.015 | 0.016 |
| Core, average | 0.107 | 0.105 |
| Inside cladding, average | 0.016 | 0.017 |
| Overall length, nominal | 119.0 | 119.0 |
| Core, tip-to-tip | 110.2 | 110.5 |

D. Extrusion Conditions

| | Tube 167 | Tube 168 |
|---|---|---|
| Tool temperature (°C) | 370 | 370 |
| Billet temperature (°C) | 725 | 720 |
| Extrusion force, running (tons) | 1070 | 1000 |
| " " , maximum (tons) | 1130 | 1100 |
| Extrusion constant, running (tsi) | 19.5 | 18.2 |
| Ram speed (inches/min) | 30 | 31 |
| Extrusion ratio | 15.4 | 15.4 |

Billets, copper-clad

Copper cutoff

E. Heat Treatment

None.

F. Autoclave Test

Half-inch ring sections from the ends of each of the three tubes were tested at 400 °C in 1500 psi steam for 14 days. Rings from tubes 167 and 168 showed indications of copper spots in the cladding as a result of copper-Zircaloy reaction during heating and extrusion of the billets. This was corrected in tube 169 by venting the copper jacket, instead of evacuating and sealing. Confirmation was in the uniform, lustrous, black oxide film on the ring from tube 169 after autoclaving.

G. Remarks

None.

33. NM Tubes Nos. 1-1 to 1-4, 2-1 to 2-3

Ref: DP-943, April 1965, S.R.Nemeth, "Thorium-1.4 w/o $^{235}$Uranium Metal Tubes, Fabrication and Irradiation in HWCTR". (Note: DP-943 Supplement contains complete data and had limited circulation.)

In connection with studies of $D_2O$ moderated-and-cooled thorium-$^{233}$uranium breeder reactors, a program was undertaken to deliver to HWCTR two pile-worthy Zircaloy-clad tubular elements of a Th-1.4 w/o $^{235}$U alloy. Four prototype Th-U tubes (1-1 to 1-4) and three enriched Th-$^{235}$U tubes (2-1 to 2-3) were fabricated. Two of the enriched tubes (2-1 and 2-3) were irradiated in HWCTR, one tube (1-3) used for flow tests at SRL, and two tubes (1-1 and 1-2) destructively evaluated. Data for tubes 1-3, 2-1 and 2-3 are presented below.

A. Description

Thick-wall thorium-uranium metal fuel tube, 2.545" OD X 0.350" wall (nominal).

B. Composition

Core: 1-1 to 1-4 - Th-1.6 w/o U (natural)
2-1 to 2-3 - Th-1.5 w/o U enriched to 93% $^{235}$U.

Cladding: Zircaloy-2 (30 mils)

End seals: Integral-type, Zircaloy-2

C. Dimensions

| | Tube 1-3 (inches) | Tube 2-1 (inches) | Tube 2-3 (inches) |
|---|---|---|---|
| Over uniform core, OD | 2.539 | 2.537 | 2.536 |
| " " " , ID | 1.840 | 1.833 | 1.831 |
| Overall length, nominal | 118.0 | 118.0 | 118.0 |
| Core tip-to-tip, nominal | 108.0 | 108.0 | 108.0 |

D. Extrusion Conditions

(Done at SRP)

| | Tube 1-3 | Tube 2-1 | Tube 2-3 |
|---|---|---|---|
| Tool temperature (°C) | 315-370(1) | 370 | 370 |
| Billet temperature (°C) | 775 | 760 | 760 |
| Extrusion force, running (tons) | --- | 1500 | 1500 |
| " " , maximum (tons) | 2000 | 1900 | 1900 |
| Extrusion constant, running (tsi) | --- | 15 | 15 |
| Ram speed (inches/min) | 12 | 12 | 12 |
| Extrusion ratio | 14.0 | 14.0 | 14.0 |

Billets, copper-clad
Copper cutoff

(1) Liner and die at 315 °C; mandrel and cutoff at 370 °C.

E. Heat Treatment

None.

F. Autoclave Test

Tubes 2-1 and 2-3 were tested at 345 °C in water for 24 hours followed by 24 hours at 400 °C in 1500 psi steam. Both tubes exhibited a uniform, black oxide surface film.

G. Remarks

None.

H. Current Condition

Tubes 1-3, 1-4 and 2-2 are stored at SRL; none are satisfactory for irradiation.

34. NM TWOT Tube Series (15 tubes)

Ref: NMI-7218-2, 8/1/65, A. B. Bremer, "Evaluation of Fifteen Outer Tubes of Zircaloy-Clad Unalloyed Uranium for the HWCTR".

Fifteen thin-wall outer tubes with unalloyed uranium cores were fabricated as part of nested concentric tubes for irradiation tests in HWCTR. Eight fuel assemblies containing these tubes were irradiated in HWCTR using spiral ribbon-type spacers. Two of the seven assemblies failed during irradiation because of fretting corrosion where the spacer contacted the tube walls. Data for three typical tubes of this group are presented below.

A. Description

Thin-wall outer tube, 2.060" OD X 0.180" wall (nominal).

B. Composition

Core: Unalloyed uranium

Cladding: Zircaloy-2 (25 mils)

End seals: Integral-type, zirconium

C. Dimensions

| | NM Tube Numbers | | |
|---|---|---|---|
| | 1 (inches) | 8 (inches) | 15 (inches) |
| Over uniform core, OD | 2.058 | 2.060 | 2.060 |
| " " " , ID | 1.693 | 1.695 | 1.694 |
| Overall length | 118.0 | 118.0 | 118.0 |
| Core, tip-to-tip | 109.7 | 109.9 | 109.3 |

D. Extrusion Conditions

| | NM Tube Numbers | | |
|---|---|---|---|
| | 1 | 8 | 15 |
| Tool temperature (°C) | 370 | 370 | 370 |
| Billet temperature (°C) | 630 | 630 | 630 |
| Extrusion force, running (tons) | 790 | 750 | 773 |
| " " , maximum (tons) | 983 | 865 | 913 |
| Extrusion constant, running (tsi) | 16.3 | 15.4 | 15.9 |
| Ram speed (inches/min) | 13-15 | 13-15 | 13-15 |
| Extrusion ratio | 15.0 | 15.0 | 15.0 |

Billets, copper-clad
Copper cutoff

E. Heat Treatment

Each of the fifteen tubes was beta-treated in its copper extrusion jacket while being rotated at 15 rpm. Heat treatment consisted of immersion for 10 minutes in a 740 °C salt bath, air-cooling for 6 minutes, then quenching in 20 °C water for 2 minutes.

F. Autoclave Test

The tubes were tested for 4 hours in 345 °C water followed by 32 hours at 400 °C in 1500 psi steam. All tubes had a continuous, lustrous, black surface film following the test.

G. Remarks

None.

H. Current Condition

The tubes of this group that were not irradiated are stored at SRL.

35. NM TWIT Tube Series (15 tubes)

Ref: NM-7218-1, 8/15/62, A.B. Bremer, "Evaluation of Fifteen Inner Tubes of Zircaloy-Clad Unalloyed Uranium for the HWCTR".

In conjunction with the TWOT series tubes, fifteen thin-wall inner tubes with unalloyed uranium cores were fabricated for irradiation in HWCTR as part of a concentric two-tube design assembly. Two of the seven assemblies irradiated in HWCTR failed because of fretting corrosion where the spiral ribbon spacer contacted the fuel tube walls. Data for three typical tubes of this group are presented below.

A. Description

Thin-wall inner tube, 1.020" OD X 0.180" wall (nominal).

B. Composition

Core: Unalloyed uranium

Cladding: Zircaloy-2 (25 mils)

End seals: Integral-type, zirconium

C. Dimensions

| | NM Tube Numbers | | |
|---|---|---|---|
| | 3 (inches) | 11 (inches) | 18 (inches) |
| Over uniform core, OD | 1.022 | 1.022 | 1.023 |
| " " " , ID | 0.656 | 0.657 | 0.658 |
| Overall length (nominal) | 118.0 | 118.0 | 118.0 |
| Core, tip-to-tip | 109.1 | 108.9 | 109.4 |

D. Extrusion Conditions

| | NM Tube Number | | |
|---|---|---|---|
| | 3 | 11 | 18 |
| Tool temperature (°C) | 480 | 480 | 480 |
| Billet temperature (°C) | 630 | 630 | 630 |
| Extrusion force, running (tons) | 380 | 373 | 430 |
| " " , maximum (tons) | 445 | 445 | 550 |
| Extrusion constant, running (tsi) | 13.9 | 13.7 | 15.8 |
| Ram speed (inches/min) | 13-15 | 13-15 | 13-15 |
| Extrusion ratio | 17.7 | 17.7 | 17.7 |

Billets copper-clad
Copper cutoff

E. Heat Treatment

Each of the fifteen tubes was beta treated in its copper extrusion jacket while being rotated at 15 rpm. Heat treatment consisted of immersion for 10 minutes in a 740 °C salt bath, air-cooling for 6 minutes, then quenching in 20 °C water for 2 minutes.

F. Autoclave Test

The tubes were tested for 4 hours in 345 °C water followed by 32 hours at 400 °C in 1500 psi steam. All tubes had a continuous, lustrous, black surface film following the test.

G. Remarks

None.

H. Current Condition

The unirradiated tubes are stored at SRL.

36. NM Tube Sets M-1 and M-2, HWCTR Driver Tubes (56 tubes)

Ref: Items 7 and 9 of this appendix.

A total of 56 driver tubes were fabricated for the HWCTR based on the process developed in making the 12 experimental tubes described in Items 7 and 9. All of these tubes had cores of Zr-9.3 w/o U enriched to 93% $^{235}U$ and Zircaloy-2 end seals. Twenty-seven tubes (Nos. 1-27) were clad with Zircaloy-2, twenty-seven (29-55) with Zircaloy-4[1] and two (56-57) were outer-clad with Zircaloy-2 and inner-clad with Zircaloy-4. The change to Zircaloy-4 was made midway during fabrication in view of the expected lesser amount of hydrogen absorbed by Zircaloy-4 by contrast to Zircaloy-2.

Three of the 56 tubes were rejected as being irradiation candidates because of minor defects; tube No. 2, outside surface bump; tube No. 11, depressions in the outer cladding; and tube No. 19, nonbond indication. Of the 13 tubes autoclaved, all were found satisfactory.

Forty-eight of the tubes were irradiated in HWCTR, 24 as the M-1 driver set and 24 as the M-2 driver set. All irradiated tubes performed satisfactorily.

Detailed data for this group of production tubes are similar to that presented under Item 9 of this appendix.

37. NM Tube Set M-3, HWCTR Driver Tubes (28 tubes)

Ref: Item 32 of this appendix.

This production group of 28 single-tube drivers were fabricated for HWCTR based on the process developed in making the three experimental tubes described in Item 32. This set was designed to permit operation of HWCTR at higher power levels than was possible with the M-1 and M-2 driver sets. All of these tubes had cores of Zircaloy-2, 11.1 w/o U enriched to 93% $^{235}U$, Zircaloy-2 cladding and integral-type, Zircaloy-2 end seals.

Of the 28 tubes, four were rejected as irradiation candidates for the following reasons. Tube Nos. 20 and 22 had depressions 5 mils deep in the 15-mil-thick cladding. Tube Nos. 23 and 25 failed the notch-fracture test at both ends, with No. 23 also failing the ultrasonic test for nonbonds. Of the 8 tubes autoclaved, all were found satisfactory.

Detailed data for this group of production tubes are similar to Item 32.

All 28 tubes are stored at SRL for use in HWCTR, should it be reactivated.

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(1) Current designation of this alloy is low nickel-Zircaloy-2