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PROCESS DEVELOPMENT AND FABRICATION
OF
ZIRCONIUM HYDRIDE
HASTELLOY X CLAD
FUEL ELEMENTS

AEC Research and Development Report

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T. G. PARKER, Jr.

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ABSTRACT

This report summarized the development work performed, and the processes established, for the fabrication of Hastelloy X clad, U-ZrH_x fuel elements. Processes described include: U-Zr alloy melting and extrusion, U-Zr hydriding, Gd₂O₃ vapor deposition on U-ZrH_x fuel rods, machining helical fins in Hastelloy X cladding, Hastelloy X electron beam welding, ceramic coating of Hastelloy X, and final assembly operations. Process and test data on developmental fuel elements are presented, which demonstrate that the dimensional and performance test requirements of the 5-kwe zirconium hydride reactor could be met.

TABLE 1
U-Zr REACTOR DESIGN DESCRIPTIONS

	SNAP 10A	S2DR	S8ER	S8DR	5 kwe
Number of Elements	37	37	211	211	85
Diameter (in.)	1.25	1.25	0.56	0.56	1.005
Length (in.)	13.0	13.0	14.5	16.0	17.0
N_H (H atoms/cc $\times 10^{-22}$)	6.5	6.5	6.0	6.0	5.7
U^{235} (wt %)	10	10	10	10	10
Total U^{235} (kg)	4.3	4.3	6.6	6.6	9.0
Cladding Thickness (in.)	0.015	0.013	0.010	0.010	0.025
Core Vessel Diameter (in.)	9.0	8.9	9.8	9.8	10.6
Core Vessel Height (in.)	15.6	16.0	21.0	23.0	-
Weight With Reflector (lb)	250	300	550	550	500
Inlet Temperature ($^{\circ}$ F)	900	1000	1100	1100	1100
Outlet Temperature ($^{\circ}$ F)	1010	1200	1300	1300	1200
Maximum Fuel Temperature ($^{\circ}$ F)	1085	1280	1450	1450	1350
Power (kwt)	34	50	600	600	100

I. INTRODUCTION

Development of the zirconium hydride (ZrH) reactor concept was initiated in 1955, as one approach to a compact, lightweight power source for space applications. This effort was conducted for the Atomic Energy Commission, as part of the Systems for Nuclear Auxiliary Power (SNAP) Program. A series of ZrH reactors have been designed, built, and operated in ground tests (i.e. SNAP 10A, S2DR, S8ER, and S8DR). In 1965, the operational capability of this type of reactor in the space environment was demonstrated by the launch and operation of a SNAP 10A in earth orbit. In each of these reactors, the sheathed U-ZrH_x fuel is arranged in a hexagonal array, with peripheral reflectors used to form a cylindrical core. The core is contained in a stainless steel vessel, and cooled by recirculation of NaK-78, the eutectic of sodium-potassium. Active control is provided by movable beryllium reflectors, mounted external to the core vessel. A general design description of these reactors is given in Table 1.⁽¹⁾ Note that, although the thermal power ranges from 34 to 600 kw, the core sizes remain compact and relatively lightweight.

The experience gained from these reactors was being applied to the design and development of a 5-kwe reactor, when the SNAP Zirconium Hydride Program was closed out in 1973. This reactor was being designed for use with a thermoelectric power conversion system, as a power source for unmanned space applications. It was to produce 100 kw of power, with a 5-year life. Detail reactor design and analyses were in progress at the time of program close-out. Parameters describing the 5-kwe reactor are listed in Table 1, for comparison with prior designs. Process development was also in progress on the fabrication of prototype fuel elements.

This report will describe the status of that fuel element development and fabrication effort.

Figure 1. Fuel Element Schematic - 5-kwe Reactor

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Figure 2. 5-kwe Reactor Core Arrangement

II. FUEL ELEMENT DESIGN DESCRIPTION

The 5-kwe zirconium hydride reactor core contains 85 fuel elements in a close-packed, hexagonal array. The elements are nominally 17.0 in. long and 1.0 in. in outside diameter. The active fuel length is 16.0 in., made up of five 3.2-in. segments. The U-Zr fuel contains 10.5 wt % enriched U^{235} , and is hydrided to an N_H^* of 5.7. The fuel rods are coated with a thin film of gadolinium oxide (Gd_2O_3), a burnable poison. As the Gd_2O_3 burns out during reactor operation, an increase in reactivity results. Gd_2O_3 was chosen because the rate of reactivity gain due to burnout closely matches the rate of reactivity loss from the core due to uranium burnup and hydrogen loss. The Gd_2O_3 coated fuel is clad in a Hastelloy X envelope, which is coated on the inside with a ceramic hydrogen barrier. Hastelloy X was chosen as the cladding material because of its high strength and excellent ceramic coatability. A low-cobalt and low-tungsten version of the Hastelloy X alloy is used to minimize parasitic neutron absorption. The internal axial gap between fuel and cladding is filled with a vibration suppressor, to minimize fuel movement during reactor space launch. The suppressor is a pedestal device which is stable during launch (low temperature), but collapses during reactor operation (elevated temperature), due to fuel-swelling-induced loads.

A combination of finned and unfinned (neutral) clad elements are used in the core to promote coolant mixing (i.e. heat transfer). Three helical fins are machined into the cladding, on a 5.0-in. pitch over 15.0 in. of the cladding length. A schematic of a finned element, with all components identified, is shown in Figure 1. Both left- and right-hand pitch fins are used. The locations of left pitch (L), right pitch (R), and neutral (N) fuel elements in the core is shown in Figure 2. With this element arrangement, there are no directly opposing coolant streams. This is illustrated in the enlarged four-element segment of Figure 2. The hexagonal profile of the finned cladding is also clearly shown in this figure. Machining these flats on the fins provides fin extension into the cusp-shaped areas between elements, minimizing streamline coolant flow and enhancing coolant mixing.

* N_H = hydrogen atoms $\times 10^{22}$ /cc of hydrided fuel

The centerline spacing of fuel elements in the core is 1.025 in. This results in a theoretical fin tip to opposing wall gap of 0.010 in., or a coolant flow channel of 0.020 in. between elements. Thermal, hydraulic, and stress analyses performed on the core assume clustering of elements during reactor operations.⁽²⁾ These analyses dictate the fin height, width, and pitch. Critical dimensions resulting from these and nuclear analyses are shown in Table 2. These dimensions control element to element spacing, and internal fuel to ceramic barrier gap. Element spacing has a first-order effect on the thermally and/or mechanically induced stresses in the ceramic-coated cladding. The tolerances specified for the cladding represent the practical limits achievable in fabricating seamless Hastelloy X cladding, both finned and neutral. Similarly, the tolerances on ceramic barrier thickness and fuel rod diameter, which control internal diametral gap, are the practical processing limits. The fuel to ceramic barrier gap is sized to allow maximum fuel rod size (fuel fraction or reactivity worth), while allowing margin for fuel swelling. It is for these reasons that the fuel rods are required to be selected to provide 0.011 to 0.013 in. diametral gap. This gap range can be met only in this way, because of the stackup of tolerances on the cladding components.

TABLE 2
FUEL ELEMENT DIMENSIONS — 5-kwe REACTOR

Cladding	
Outside diameter (in.)	1.005 ± 0.004
Fin height (in.)	0.050 ± 0.001
Fin width (in.)	0.125 ± 0.005
Wall thickness (in.)	0.025 ± 0.0015*
Ceramic Hydrogen Barrier	
Thickness (in.)	0.0025 ± 0.0005
Inside diameter (in.)	0.950 ± 0.002
Fuel Diameter (in.)	0.938 nominal [†]
Fuel-Ceramic Diametral Gap (in.)	0.012 ± 0.001

*Finned elements only — neutral are ±0.001

[†]Fuel diameter selected to provide the 0.011 to 0.013 in. diametral gap

In-process and final inspection assure that the fuel elements conform to the required design dimensions. However, the final acceptance test is the measurement of hydrogen permeation or loss rate from the fuel element at elevated temperature. For the 5-year life of the 5-kwe reactor, the average hydrogen loss rate must be 0.54 cc (STP)/hr or less,* to produce 100 kwt of power over the entire 5-year life. If this rate is exceeded, the reactor will produce less than rated power during late life, while a smaller rate will allow a longer operating life. Prior to production of fuel elements for a core, developmental and prototype elements are subjected to vibration, cyclic and static bending, thermal transients, and thermal aging tests, as a means of assessing performance in the reactor environment. Hydrogen permeation tests, conducted before and after these inputs, are used to assess damage. Data from these tests are used to define lifetime (hydrogen retention) capability of the fuel elements, for incorporation in nuclear design analyses.

*Measured at 1300° F isothermal temperature

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Figure 3. Hastelloy X Fuel Element Fabrication Flow Chart

III. FUEL ELEMENT FABRICATION PROCESS

The fuel element assembly consists of five fuel rod segments, a vibration suppressor, either finned or neutral cladding, an end cap, and a cup plug (see Figure 1). The assembly procedure is as follows. The cladding tube is ceramic coated on the inside, and welded to a ceramic-coated end cap. This subassembly is coated a second time with ceramic, and the fuel rods and vibration suppressor are loaded. A ceramic-coated cup plug is shrunk fit into the cladding tube, and a final gastight seal is made by fusing the ceramic between the cup plug and cladding tube. The latter operations are done in a helium atmosphere. Finally, a structural joint is made by electron beam welding the cup plug to the cladding tube.

There are a number of processing steps involved with each of the element components. The cladding is extruded in 0.025 in. wall for neutral cladding, and 0.075-in. wall for machining into finned cladding. Cladding is then out-gassed, sandblasted, and oxidized, in preparation for ceramic coating. These same steps are used in preparing cup plugs and end caps for coating. The fuel is prepared by a triple-arc-melt, double-extrusion process. The extruded fuel rods are hydrided, machined to size, and then vapor coated with Gd_2O_3 . A flow chart for the overall fuel element fabrication is shown in Figure 3. The following sections describe in detail each of the process steps.

A. CLADDING

Hastelloy X, low in cobalt and tungsten, was selected as the cladding material. This selection was based initially upon a review of the literature on candidate alloys, and finally on properties tests.⁽³⁾ Concurrent with these activities, a heat of Hastelloy X tubing was being procured and the fin machining processes were being developed.

1. Bar and Tubing Procurement

Fabrication of seamless tubing was initiated with the procurement of a heat of Hastelloy X (~6000 lb). Approximately 5000 lb was in the form of 2-1/8 in. bar, for conversion into tubing; the balance was 1-1/8-in. bar, to be used for machining end caps and cup plugs.

The heat chemistry is shown in Table 3, in comparison to the specified alloy chemistry. The bar was delivered in the fully solution annealed condition. A grain size of ASTM 6 or smaller was specified, with no duplex structure allowed. Room temperature tensile yield strength and ductility were specified to be at least 45,000 psi and 35%, respectively. These properties are specified to assure good workability in subsequent drawing operations.

TABLE 3
HASTELLOY X CHEMISTRY
(Heat No. 1323)

Element	wt %	
	Specified	Heat No. 1323
Iron	17.0 - 20.0	19.7
Chromium	20.5 - 23.0	20.1
Nickel	Balance	Balance
Boron	0.001 max.	0.0005
Sulphur	0.010 max.	0.003
Manganese	0.70 max.	0.14
Cobalt	0.20 max.	<0.01
Nitrogen	0.020 max.	0.007
Carbon	0.06 - 0.12	0.10
Silicon	0.4 - 1.0	0.80
Molybdenum	8.0 - 10.0	9.0
Oxygen	0.020 max.	0.001
Tungsten	0.50 max.	0.02
Phosphorus	0.020 max.	0.008

The 2-1/8-in. bar was machined on the outside, and then gun drilled and honed to produce draw shells. The dimensional specifications for draw shells are:

Length (ft)	1 to 4
Inside diameter (in.)	1.425 ± 0.001
Wall thickness (in.)	0.312 ± 0.009
Surface finish (rms)	63 or better

A total of 425 ft of bar was processed to tube hollows. The overall material yield was $\sim 45\%$. Although this is a low material yield, it is a cheaper process for draw shell fabrication than extrusion followed by machining. Extrusion saves material, but costs more in tooling and manhours.

The draw shells were shipped to a vendor for reduction into seamless tubing. The dimensional specifications imposed for the two sizes of tubing are:

Wall (in.)	0.025 ± 0.0015	0.075 ± 0.004
Inside diameter (in.)	0.955 ± 0.001	0.955 ± 0.001
Ovality (in.)	0.004 max.	0.004 max.
Bow (in./ft)	0.005 max.	0.005 max.
Finish (rms)	32 min	32 min

Solution anneal is the final heat treatment specified for the tubing. A grain size of ASTM 6 or finer is required, with no duplex structure. The acceptance levels for tensile yield strength and ductility are 45,000 psi and 35%, respectively. The finished tubing was source inspected, and met these requirements, demonstrating that tubing can be fabricated to the dimensions and quality required for reactor fuel elements.

2. Fin Machining

An attempt was made initially to procure drawn or extruded cladding with integral fins. The helical fin geometry and tight tolerance met negative response from tubing vendors. Machining of fins by conventional milling techniques was deemed prohibitively expensive, so other machining approaches were pursued. A gear hobbing machine shop was contacted, to discuss the cladding fabrication problem. It was thought that extension of the technique (hobbing), used for cutting spiral tooth gears, might be adaptable to finned tube fabrication. Initial work with Incoloy 800 tubing demonstrated the feasibility of this approach. The gear hobbing machine used is shown in Figure 4.

The machine has three basic movements:

- 1) Rotation of the tubing between centers
- 2) Rotation of the hob cutter
- 3) Translation of the hob cutter axially along the tube.

Figure 4. Hob Machine and Tooling 6531-1815

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Figure 5. Fabrication of Finned Cladding

The setup of a part in the machine, and the machine movements, are shown schematically in Figure 5. The part is mounted on a mandrel or arbor, to help minimize bowing and ovality during machining. The tube is mounted between rotating centers, adjusted to be parallel to the machine ways (similar to lathe setup). To further reduce bowing, the tube is supported by a cylindrical bushing, immediately ahead of the cutter. This bushing is adjusted to be in line with the rotating centers. The bushing and hob cutter are attached to the machine carriage, and translate along the tube together. The hob cutter is indexed to the cutting depth required to achieve the desired root wall thickness, and then all three helical fins are generated in a single pass along the tube. A view of the cutter at completion of a tube is shown in Figure 6.

Developmental hobbing work was done with available Hastelloy X tubing, (i.e., 0.540 or 0.651 in. ID, with nominal 0.050 in. wall). The target root wall thickness was 0.028 ± 0.001 in. for all of the tubes produced. Five lots of finned tubing were machined. Wall thicknesses of starting and finished tubes were measured, and analyzed statistically. The results of these analyses are presented in Table 4. These data indicate that, for a given machine setup, the reproducibility is excellent. The last two lots were machined with a carbide-tipped hob, which significantly improved tool life and improved machine alignment techniques. These items explain the improved control of nominal wall thickness. For all of these lots, an 0.004-in. undersize mandrel and an 0.002-in. oversize bushing were used.

Hobbing development was terminated before any 1-in. Hastelloy X tubing was received. However, capability in machining 0.050-in. high fins on this size was demonstrated with stainless steel tubes. Measurements taken on two of these tubes are shown in Table 5, and machined tubes are shown in Figure 7. These tubes were used to initiate the development of the hexagonal fin profiling operation. Tooling was completed, and tubes were fabricated in a milling operation (see Figure 8). This preliminary work indicated the feasibility of milling accurately indexed hex flats to the required tolerance.

6531-1819

Figure 6. Hob Machine Tooling

TABLE 4
HOBBED HASTELLOY X CLADDING DIMENSIONS

Lot	Tubes	Starting Wall		Hobbed Wall	
		Thickness (in.)	2σ (in.)	Thickness (in.)	2σ (in.)
1	6	0.0507	0.001	0.0282	0.0014
2	4	-	-	0.0268	0.0016
3	9	-	-	0.0293	0.0012
4	21	0.0635	0.0008	0.0289	0.0014
5	10	-	-	0.0286	0.0012

TABLE 5
HOBBED STAINLESS STEEL TUBING DIMENSIONS

	Fin Width (in.)	Helix Length (in.)	Root Diameter Finned Area (in.)	Root Diameter Unfined Ends (in.)
Requirement	0.125 ± 0.010	5.00 ± 0.030	1.000 ± 0.002	1.000 ± 0.002
Tube No. 1	0.123	5.00	1.0020	0.9978
	0.123	5.00	1.0008	0.9988
	0.123	5.00	1.0000	0.9997
	0.127		0.9998	1.0000
	0.125		1.0001	0.9978
Tube No. 2			0.9991	
			1.0005	
			1.0004	
			0.9992	
			1.0010

Figure 7. Hobbed Stainless Steel Tubing
(1.0 in. diameter)

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Figure 8. Hobbed Tube Hex Profile Milling

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B. CERAMIC HYDROGEN BARRIER

1. Ceramic Fabrication

The ceramic coating selected for the fuel elements is designated SCB. It was selected from a group of ceramics that were formulated and tested for cladding coatability, service temperature (up to 1400° F), and hydrogen retention capability. The ceramic fabrication process involves smelting of materials to obtain "frit," and subsequent addition of additives to obtain the "slip" used in coating cladding components. The frit is composed of 45% SiO₂, 35% BaO₂, 7% Al₂O₃, and 13% TiO₂. It is smelted at 2800° F, quenched in distilled water, and milled to a No. 35 mesh size. The slip is formulated in batches, using the following materials in the quantities shown:

<u>Material</u>	<u>Weight (gm)</u>
Frit	500
Ferro Black Label Clay	15
Chrome Oxide	5
Bentonite	1.25
Distilled Water	250

This aqueous slurry, ball milled to a No. 325 mesh size or finer, constitutes a batch of SCB slip.

2. Component Preparation

The preparation procedures for coating cladding, end caps, and cup plugs are basically the same. These include outgassing, grit blasting, and oxidizing the substrate. Outgassing is specified to minimize gas emitted during high-temperature firing of the SCB slip. Grit blasting is done to enhance mechanical bonding of the ceramic to the substrate. The oxidation step provides a thin chemical bond of the ceramic to the substrate. The process parameters for these steps are:

- 1) Outgassing, 30 min at 1750° F and 10^{-4} torr
- 2) Grit blasting, 35 mesh Al₂O₃, two passes
- 3) Oxidation — flowing 55% Ar - 45% O₂ gas, 1950° F for 15 min for cladding, or 1900° F for 3-1/2 min for end fittings.

Figure 9. Grit Blasting Apparatus

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Figure 10. Ceramic Coating Apparatus

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The grit blasting is done with tooling specially designed to control grit angle of attack, dwell time in a given area, and flow rate (see Figure 9). The oxidation step is performed on individual components loaded in quartz retorts. The Ar-O₂ gas flow through the retort is controlled at 575 cc/min during firing and cool down after removal of the retort from the furnace.

3. Ceramic Coating Process

The SCB slip is applied, using a technique illustrated in Figure 10. The cladding is suspended inside a sealed quartz retort which extends below the surface of the slip in the tank. With the tank vent closed, air pressure is introduced into the tank, forcing the SCB slip up inside the quartz retort and cladding tube. When SCB slip starts draining from the overflow tube, the air pressure is removed and the slip returns to the tank. For end fittings, the slip is applied manually with a spray gun. Slip application is followed by at least 15 min drying time at room temperature. Weight measurements are taken to determine the amount of slip retained. Slip weight is an in-process measure of expected thickness of the fired ceramic. If the slip weight is within specified limits, the components are fired in air at 2150° F for 4-1/2 min, and air quenched. The coated tube then has a coated end cap welded to it, prior to the second or final coating application. The final coated tube is dimensionally inspected and visually examined for uniformity of coating color and to assure the coating is pit free. Welding of a coated end cap to a coated cladding tube is required to meet the 0.0025 ± 0.0005 in. thickness specified for the 5-kwe reactor. Standard SCB coating practice was to double-coat tubing after the end cap was welded in place. This results in a tapered SCB thickness, thin at the end cap and thick at the open end. In the current process, a coated end cap is welded to the end of the cladding tube having the thicker ceramic after first coating. The tube is then second coated, using the procedure previously described. This results in a compensating taper and a uniform SCB coating thickness. This procedure is referred to as the reverse drain process. The achievable control of SCB thicknesses for the respective processes is shown in Figure 11.

4. End Cap Welding

The coated end cap and cladding tube are joined with an electron beam weld. The coated parts are machined and polished to produce flat, normal, mating faces,

Figure 11. SCB Coating Thickness Limits, Reverse Drain vs Standard Coating Process

a. Interface Over Weld Zone

b. Interface Adjacent to Weld Zone

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Figure 12. Hastelloy X - SCB Butt Weld Interface

with sharp, chip-free SCB coating. The parts are vapor degreased, ultrasonically cleaned in distilled water (145°F), rinsed in ethyl alcohol, and air dried. The components are tack welded together in a fixture which assures minimum mismatch of the mating faces. The electron beam weld is then made in the Hastelloy X cladding. The heat from the welding fuses the ceramic, making a good, crack-free, hydrogen-retaining joint.

Photomicrographs of this type joint are shown in Figure 12. Note that the oxide substrate on the cladding is still retained after the weld is made. The joint shown is on a 0.540-in. ID Hastelloy X tube with 28 mil wall; no welding tests were made on the 1.0-in. diameter reactor tubing, due to program close-out.

C. FUEL

The fuel rod fabrication for the 5-kwe reactor involves triple arc melt and double extrusion of alloy material, hydriding, machining to size, and finally, vapor deposition of Gd_2O_3 on the rod surface. A general flow chart for these operations is shown in Figure 13. Details on the respective operations follow.

1. Fuel Melting and Extrusion

The fuel alloy is composed of zirconium - 10.5 wt % enriched uranium, with 0.15 wt % carbon added as a grain refiner. The alloy is prepared by a triple consumable-arc melt, double-extrusion process, to assure that the uranium is distributed homogeneously. The fuel materials are:

- 1) Zirconium sponge, 99.6 wt % Zr, with impurities limited as noted in Table 6, and particle size within minus 3/8 inch and plus No. 20 mesh
- 2) Uranium pellets, 93% enriched in U^{235} , with total uranium at least 99.95 wt % and impurities as noted in Table 7.
- 3) Zirconium carbide, No. 325 mesh or smaller particle size, total impurities <5000 wppm, with boron and hafnium limited to 2 and 100 wppm, respectively.

The initial step is to compact the feed material in a die, at 500 or more tons pressure, to form compacts. The compacts, nominally 1-1/2 by 10 in. long, are TIG welded together to form a consumable arc melt electrode. The electrode size is limited by criticality considerations, and the requirements to have

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Figure 13. Fuel Rod Fabrication — Process Flow Chart

TABLE 6
ZIRCONIUM IMPURITY
LEVEL LIMITS

Element	Maximum Level (ppm by weight)
Aluminum	60
Boron	0.5
Cadmium	0.5
Calcium	30
Carbon	150
Chlorine	500
Chromium	100
Cobalt	5
Copper	20
Hafnium	100
Iron	500
Lead	10
Lithium	1
Magnesium	100
Manganese	30
Molybdenum	10
Nickel	50
Nitrogen	30
Oxygen	1000
Phosphorous	50
Silicon	100
Sodium	50
Titanium	30
Tungsten	50
Vanadium	20
Zinc	50
Total Rare Earths	15

TABLE 7
URANIUM IMPURITY
LEVEL LIMITS

Impurity	Maximum Level (ppm by weight)
Aluminum	20
Boron	1
Barium	10
Beryllium	1
Bismuth	1
Carbon	200
Calcium	25
Cadmium	1
Cobalt	5
Chromium	30
Copper	50
Hafnium	50
Iron	150
Lead	5
Magnesium	50
Manganese	25
Nitrogen	100
Nickel	100
Oxygen	200
Silicon	100
Silver	1
Sodium	10
Tin	5
Titanium	5
Tungsten	50
Vanadium	5
Zinc	50
Zirconium	10

Figure 14. Proposed U-Zr Melting and Extrusion Sequence for 5-kwe Reactor

at least 0.5 in. clearance with the melt crucible wall. Arc melting is done under vacuum, and is initiated at a pressure of 10μ . The electrode is melted into a water-cooled (45 to 50 gpm) crucible.

The flow chart for the melting-extrusion sequence to be used for 5-kwe reactor fuel is shown in Figure 14. After each melt operation, the ingot is machined to remove surface impurities. The parenthesized $\pm$ numbers in this figure represent the estimated starting melt charge (+) or machining loss (-). In fabricating the final melt electrodes from the 1-in. extruded rod, the segments are alternately oriented, end for end, from the direction in which they were extruded. This is one more step toward ensuring homogeneous uranium distribution in the succeeding melt. Melting parameters for various size electrodes are given in Table 8.

TABLE 8
CONSUMABLE ARC MELTING PARAMETERS

Electrode Size and Description	Amperage	Voltage
1.5-in. ² compact	2800-3000	26-28
3.0-in. diameter ingot	3800-4000	26-28
3 clustered 1.0-in. diameter rods	3800-4000	26-28

No limit is placed on the initial extrusion reduction ratio. However, the final extrusion must have at least 10:1 reduction. Extrusion may be performed by either copper jacketing or glass coating the extrusion billet. In either case, the following parameters are used: (1) billet preheat soak at $1000 \pm 25^\circ \text{F}$ for 1.5 to 2.0 hr, (2) extrusion die temperature of $600^{+75}_{-0}^\circ \text{F}$, and (3) extrusion ram speed of 4 to 5 in./min. The very slow extrusion speed is necessary with the U-Zr alloy to avoid surface tearing, which cannot be tolerated in the hydriding operation and must be machined off. The final extrusion is cleaned of die lubricant, and machined to 18 in. lengths for hydriding. A sample is taken from each extruded rod for isotopic analysis during the machining operation.

2. Hydriding

Hydriding is done in eight individual systems, each comprised of a hydriding retort furnace, vacuum pumping station, hydrogen supply reservoir, and programmable pressure-temperature controls. For insertion into the hydriding

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Figure 15. Hydriding System Schematic

retort, the rods are inserted in alumina tubes, with getter plugs of compacted zirconium chips inserted in both ends. The alumina tubes are oversized by about 10%, to allow for fuel rod growth due to hydriding. A schematic of the fuel load arrangement in the hydriding retort is shown in Figure 15. The hydriding retort is 4 in. in diameter, fabricated of 0.25-in. wall Hanes 25, and is rated for service pressures of 10 atm at 1800° F. Six fuel rods may be hydrided per retort, for a total of 48 per system load.

The hydriding cycle is initiated by evacuating the retort to at least 1×10^{-5} torr, and then checking in-leakage. In-leakage must be $<10 \times 10^{-3}$ torr, to allow hydriding to proceed. While holding vacuum, the temperature is increased to $1650 \pm 25^\circ \text{F}$. Hydrogen is admitted to the retort when an axial temperature profile within $\pm 10^\circ \text{F}$ of the set temperature is achieved. The hydrogen gas used is 99.999% pure, with no more than 10 ppm oxygen, a dew point of -97°F , and no more than 12 ppm water at -97°F . The hydrogen pickup in the fuel is controlled by correlation to pressure drop in the closed (fixed volume) system. Hydriding rate is critical, and is controlled to a slow, uniform rate. At least 6 hr must be used to reach a hydrogen to zirconium atom ratio (H/Zr) of 1.0, and an additional 12 hr to reach an H/Zr of 1.5. These two steps bring the fuel through the β and $\beta + \delta$ hydride phases, [see Figure 16⁽³⁾]. Longer times may be used, but shorter times result in formation of large columnar grains, radial hydrogen gradients, and a high incidence of cracked rods, all of which are highly undesirable. Hydriding in the δ - or ϵ -phase region (>1.5 H/Zr) is accomplished at 1400° F. The temperature is dropped from 1650° F, at a rate of $20 \pm 5^\circ \text{F/hr}$ and stabilized at 1400° F. Hydriding proceeds until the target H/Zr is reached (i.e., 1.62 H/Zr for the 5-kwe reactor fuel). Cooldown is initiated and controlled at $20 \pm 5^\circ \text{F/hr}$ to 1200° F, when the furnace is turned off. During cooldown, the pressure is regulated, based on the hydrogen disassociation pressure-temperature curve (isochore) for the target H/Zr. A parametric plot of isochores for the entire range of H/Zr ratios is shown in Figure 17.⁽¹⁴⁾ The actual hydrogen content of the fuel is determined, based on weight gain, as determined by measurements taken before and after hydriding. Weight measurements are made to the nearest 0.01 gm. This method is more accurate than other methods, such as vacuum outgassing, which utilize small sample sizes.

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Figure 16. Zirconium Hydride Phase Diagram⁽³⁾

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Figure 17. Dissociation Pressure Isochores for Zirconium Hydride⁽⁴⁾

After inspection of the hydrided fuel, the rods are centerless ground to within ± 0.0005 in. of the target diameter. The ground rods are segmented into lengths of 3.200 ± 0.005 in., and the edges are turned to a 0.090 ± 0.030 in. radius. The segments are inspected, etched with an identification number, and weighed.

3. Gd₂O₃ Coating

The fuel rods for the 5-kwe reactor are coated with a thin film of natural Gd₂O₃, which has a nuclear worth of \$3.00 at operating temperature. The film is applied by electron beam evaporation of Gd₂O₃ powder, and deposition of the vapor on the fuel rod surface. The film surface density required is 0.547 mg/cm² of surface, or a nominal thickness of 0.45 μ . The vapor deposition chamber is equipped with a carousel-type fixture, with the fuel segments arranged as spokes in a wheel. A secondary drive rotates the segments on their axes as the carousel rotates normal to the chamber base. Vaporization crucibles, heated by bent beam electron guns, are located in each quadrant of the carousel, in line with the center of the fuel rod length. The deposition process involves preheating the fuel rods for 20 min at 400° F, deposition of the Gd₂O₃ film, soaking the coated fuel rods for an additional 20 min at 400° F, and then cooling to room temperature. The coating process is conducted at 10^{-5} torr.⁽⁵⁾ The Gd₂O₃ film thickness is monitored during deposition with a quartz crystal detector, which is coated simultaneously with the fuel rods. The change in vibration frequency of the crystal, caused by coating application, is correlated to coating thickness on the fuel rods. Three additional checks for Gd₂O₃ mass analysis were developed, and demonstrated to be very accurate.

- 1) Wet Chemistry — A study was made of wet chemistry accuracy by preparing standards of known Gd₂O₃ concentration and analyzing them. An accuracy within $\pm 1\%$ was demonstrated.
- 2) X-Ray Fluorescence (XRF) — Fuel rod surfaces were fluorescenced, and the peak heights measured were found to be accurately correlatable to the mass of Gd₂O₃ present. Verification tests were performed in which coated rods were fluorescenced, Gd₂O₃ mass calculated, and then compared to the mass determined by wet chemistry on the leached coating. An accuracy of greater than $\pm 5.0\%$ was demonstrated.

- 3) Thickness Measurement — Glass rods with masked areas were coated simultaneously with fuel rods. After removing the mask, the thickness of the coating was measured with a diamond stylus instrument. A correlation between thickness and Gd_2O_3 present was developed, using wet chemistry as the correlation method. The Gd_2O_3 (in gm/cm^2) determined from thickness and surface area measurements indicated an accuracy of $\sim \pm 2\%$.

Of these methods, x-ray fluorescence is recommended for production application on a 100% inspection basis. The accuracy is adequate, and it is the least expensive of the three techniques to use. The other two methods require the use of coated and/or masked glass rods, with the assumption that the coatings applied are representative of those on the fuel rods.

The stability and adherence of the Gd_2O_3 coatings have been demonstrated in a series of thermal and mechanical tests. Coated fuel rods have been thermally aged in fuel elements for over 16,500 hr at 1400°F with virtually no evidence of spalling or chemical reaction with the fuel-barrier. Fuel elements containing coated rods also have been vibration tested to evaluate this environment. Less than 1.0% loss of Gd_2O_3 was observed. This is assumed to be due to rotation of the fuel rods against the barrier. Finally, low-hydrogen-content rods were coated, aged for 2079 hr at 1300 or 1400°F , and then hydrided to simulate fuel swelling which will occur during reactor operation. Diameter increases of 3 to 4% were induced ($\sim 11\%$ volume increase). No evidence of spalling was observed.⁽⁵⁾

D. FUEL ELEMENT ASSEMBLY

Assembly of components into the fuel element is comprised of four operations:

- 1) Loading 5 Gd_2O_3 coated fuel rods and the vibration suppressor into the SCB-coated cladding tube
- 2) Shrink fitting an SCB-coated cup plug into the cladding
- 3) Fusing the SCB coating on the cup plug to the SCB coating on the cladding
- 4) EB welding the cup plug to the cladding tube.

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Figure 18. Final Closure Fitup Tolerances

TABLE 9
FUEL ELEMENT VIBRATION TESTING

Element Number	Axial Gap (mils)	Permeation Rate [cc(STP)/hr at 1300° F]	
		Pre-Vibration	Post-Vibration*
X-35	5	0.37	0.20
X-41	15	0.18	0.36
X-58	0	0.26	0.23
X-61	0	0.41	0.32
X-60	0	0.70	0.65 (Control)

*Saturn V inputs

A schematic of the final closure, with critical fitup tolerances noted, is shown in Figure 18. The internal gap between the fuel - vibration suppressor stack and the cup plug was established, based on a series of fuel element vibration tests. Fuel elements with 0-, 5-, and 15-mil axial gap were subjected to Saturn V launch inputs. One element went through all operations except the actual vibration inputs, to provide a control. Results are shown in Table 9. An axial gap of 0 to 10 mils was selected, based on these data and tests conducted on earlier vintage fuel elements. To achieve this gap, the fuel - suppressor stack height is measured, and the cladding is machined to the proper length. The 0.5 to 1.0 mil interference between the SCB-coated cup plug and the cladding is obtained by selection of components. This tolerance was established empirically, using permeation testing to judge the quality of the joints fabricated. The 0.0 to 0.5 mil interference for the weld joint also was established empirically. In this case, metallography on joint sections was used to establish parameters yielding a crack-, void-free weld with 100% penetration. Visual and dye penetrant inspection were used to detect surface pits, cracks, and shrinkage. The latter inspection techniques are supplemented during production operations by destructive sampling, to insure the weld process remains in control. This is necessary, since x-ray, due to the geometry, does not provide adequate inspection of this weld.

The shrink fit and fusing operations are done in 0.1 atm of helium (the helium is included to provide better heat transfer characteristics for reactor startup; it is not a process requirement). The cladding tube, with fuel and vibration suppressor in place, is loaded vertically into a retort - holding fixture. The cup plug is held in a movable collet, immediately above the mouth of the cladding tube. The retort is evacuated to at least 10^{-4} torr, and backfilled with helium. Closure operations are then initiated. The upper inch of the cladding tube is induction heated in a controlled ramp. The cup plug is pneumatically driven into the cladding tube when the cladding temperature reaches the 1600 to 2000° F range. Heating is continued to $1975 \pm 75^\circ \text{F}$, and this temperature is maintained for 1.5 ± 0.5 min. The power is then turned off. The element is transferred to the EB welder, and the final weld is made. Weld and dimensional inspection completes the fabrication operation.

TABLE 10
HASTELLOY X DEVELOPMENTAL ELEMENT
PERMEATION DATA

Element Number	Element Type	Permeation Rate [cc(STP)/hr at 1300° F]
X-93	Neutral	0.13
-94	Neutral	0.14
-95	Neutral	0.15
-96	Neutral	0.18
-97	Neutral	0.17
-98	Neutral	0.12
X-63	Finned	0.17
-64	Finned	0.14
-65	Finned	0.11
-66	Finned	0.10
-67	Finned	0.11
-68	Finned	0.15
-69	Finned	0.18
-70	Finned	0.11
-71	Finned	0.18
X-72	Neutral	0.09
-74	Neutral	0.09
-75	Neutral	0.14
-76	Neutral	0.10
-77	Neutral	0.11
-78	Neutral	0.15
-79	Neutral	0.09
-80	Neutral	0.09

IV. FUEL ELEMENT PERFORMANCE

The final acceptance test on the fuel element is the measurement of hydrogen permeation rate. This is done at an isothermal temperature of 1300° F. Testing with the temperature profile of the operating reactor (1100 to 1200° F gradient) is not meaningful, because the leak rate is below the sensitivity of measuring instruments. No fuel elements of the 5-kwe reactor design were fabricated, due to close-out of the program. However, a series of nominal 0.6-in. diameter finned and unfinned fuel elements were fabricated and tested, to demonstrate the process planned for the 5-kwe fuel elements. The initial permeation test results on the 23 elements fabricated are shown in Table 10. The elements are tabulated in the order of fabrication. Analysis of these permeation rates indicates little bias between neutral and finned elements. The distribution of rates is virtually the same, as indicated in Figure 19. Another plot, Figure 20, shows the distribution and average permeation rate for the entire semi-production run of elements. Normalizing these data to the geometry (surface area) and fuel composition of the 5-kwe fuel element results in an average rate of 0.47 cc(STP)/hr. This compares very favorably with the 1300° F permeation rate of 0.54 cc(STP)/hr design requirement of the 5-kwe reactor.

Fifteen of the fuel elements were selected for thermal and thermal-mechanical testing. Twelve were placed in a thermal aging-cycling test series. Initially, these elements were given five cycles of the thermal transient shown in Figure 21. Thermal aging was initiated with eight elements at 1250° F, and four at 1050° F. Permeation rates were measured after the thermal transients, and at 500-hr thermal aging intervals. The tests, planned for 10,000 hr, were discontinued after 1000 hr aging due to program close-out. However, the initial permeation test data, shown in Table 11, illustrate the general stability of the elements under the thermal transient stresses and limited aging.

Two other fuel elements were subjected to cyclic load tests: one at 1100° F, and one at 1200° F. With the ends pinned, a lateral load was applied at midpoint, at a rate of ~10 cycles/hr. The deflection was ± 0.050 in. about the null point. This is more than is anticipated in 5-kwe reactor, and is equivalent to ~18,500 psi tensile stress in the cladding-ceramic composite. The permeation rates

Figure 19. Permeation Rate Comparison - Finned vs Neutral Elements

Figure 20. Element Permeation Rate Distribution

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Figure 21. Thermal Transient Cycle

TABLE 11
THERMAL CYCLING-AGING PERMEATION
TEST RESULTS

Element Number	Type	Temperature of the Endurance Test (° F)	Permeation Rate [cc(STP)/hr]			
			Acceptance	Post-Transient	Post-500 hr	Final
X-64	Finned	1250	0.14	0.11	0.11	0.13
X-65	Finned	1250	0.11	0.10	0.12	0.12
X-66	Finned	1250	0.10	0.07	0.10	0.10
X-68	Finned	1250	0.15	0.07	0.10	0.11
X-72	Smooth	1250	0.09	0.13	0.15	0.15
X-74	Smooth	1250	0.09	0.11	0.14	0.15
X-75	Smooth	1250	0.14	0.12	0.17	0.19
X-76	Smooth	1250	<u>0.10</u>	<u>0.14</u>	<u>0.11</u>	<u>-</u>
Average			0.115	0.106	0.125	0.133
X-69	Finned	1050	0.18	0.08	0.08	0.13
X-70	Finned	1050	0.11	0.07	0.08	0.13
X-77	Smooth	1050	0.11	0.10	0.17	0.14
X-78	Smooth	1050	<u>0.15</u>	<u>0.08</u>	<u>0.11</u>	<u>0.13</u>
Average			0.138	0.083	0.110	0.133
Total Average			0.123	0.098	0.120	0.133

were measured before and after the tests, as a measure of any damage. No change in permeation of either element was noted after 1391 cycles. A third element was tested at 1100° F for 400 cycles, with a deflection ranging from 0.060 to 0.070 in. No damage was induced, even at this high-deflection (stress) level. The performance of these elements demonstrate the capability to withstand transient stresses far in excess of those projected for the 5-kwe reactor.⁽²⁾

The development work on fuel element fabrication has demonstrated that Hastelloy X clad, U-ZrH_x fuel elements of excellent quality can be produced. All facets of processing have been demonstrated with the production of 0.6-in. diameter fuel elements. Testing on these fuel elements, though limited, indicates a performance that should meet or exceed the requirements of the 5-kwe design. Scaleup to the nominal 1.0-in. diameter fuel element for the 5-kwe reactor should present no significant problems.

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