FUEL ELEMENT DEVELOPMENT
FOR
PIQUA OMR

By
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CONTENTS

	Page
Abstract	vi
I. Introduction	1
II. Fuel Alloy Development, Evaluation, and Selection	4
III. Melting and Casting	8
IV. Nickel Plating and Cladding	11
V. Hot Pressure Bonding	20
VI. Bond Evaluation and Testing	23
VII. Final Assembly	27
VIII. Out-Of-Pile Testing	30
IX. In-Pile Testing	35
X. Conclusions	45
References	46

TABLES

I. Results of Tensile Tests at 900°F	6
II. Results of Creep Tests of Various Alloys	7
III. Nickel Plating Procedures for Flat Plates	12
IV. Nickel Plating Procedures for U - 3.5 Mo Cylindrical Cores	16
V. Tubular Aluminum Cladding Surface Preparation	18
VI. Type 6061 Aluminum End Plug Surface Preparation	25

FIGURES

1. Eighty-Plate OMR Fuel Element (7500-5144)	2
2. Tubular OMR Fuel Element	3
3. Typical U Alloy OMR Fuel Plates, Cast to 0.130-in. Thickness	8
4. Top of Mold for Casting Six Cylinders of U - 3.5 Mo Alloy (7508-4727G)	9
5. Mold for Casting Tubular Sections, Showing Graphite Cores (7508-4727H)	9

FIGURES

	Page
6. Eight Castings for Tubular Element (7508-4714C)	10
7. Plating Rack for Flat Plate - Movable Contact Type	11
8. Flat Plate Aluminum Cladding	14
9. Hot-Knifing Apparatus.	15
10. Components of Flat Plate Fuel Section (7500-5112A).	15
11. Plating Rack for Tubular Fuel Cores - Movable Contact Type (7519-5142A).	16
12. Tubular Aluminum Cladding (7515-51267A).	17
13. Components of Tubular Fuel Section (7515-51349D)	17
14. End View of Welded End Plug and Sealed Off Evacuation Tube for Tubular Sections (7515-51349A)	19
15. Hot Pressed Tubular Sections (7515-51349B)	19
16. Components of Tubular Section, Showing Evacuation Tube Welded to End Plug (7515-51349E)	21
17. Water Cooled Copper Chill Blocks for Welding Tubular End Closures (7010-5103C)	21
18. Typical Al-Ni-U Diffusion Bond Zone, Isostatically Pressed at 1000°F and 8000 psi for 10 min	24
19. Typical Bond Zone, End Plug Nickel Plated to Cladding	24
20. Bond Zone of Hot Pressed Type 6061 End Plug to Type 1100 Cladding.	24
21. Eighty Plates, Assembled for Full-Size Flat Plate Element (7515-5110A)	26
22. Complete Flat Plate Element (7515-5111C)	26
23. Tubular Sections, Assembled for Full-Size Element (7515-4709E)	28
24. Complete Full-Size Tubular Element (7515-4709F)	28
25. Three Plates, After Exposure in Organic Loop at 800°F (7515-51319)	30
26. Partially Decanned Flat Plate Element, After Exposure in Organic Loop at 800°F (7515-51302C)	31
27. Tubular Element, After Exposure in Organic Loop at 750°F (7010-5102C).	32

FIGURES

	Page
28. Partially Decanned Tubular Element, After Exposure in Organic Loop at 750°F (7010-5101)	32
29. Fuel Sections and Boron Steel Section for HB-1 (7500-5166B)	34
30. Two Bundles of Fuel, Showing Thermocouple Arrangement for HT-1 (7515-5103A)	34
31. End View of HT-1 (7500-1806A)	36
32. Complete Element, Typical of HB-1, HB-2, and HB-3 (7515-51211B)	36
33. Bottom End of Fuel Stack of HB-1, After Removal from OMRE (7515-5143-13)	37
34. HB-1, After Irradiation, Showing Molten Cladding (7515-5144-14)	37
35. HB-2 Fuel Section (7515-51211A)	40
36. HB-2 Fuel Section Plus Boron Steel Sections, Showing Thermocouple Arrangement (7515-51179)	40
37. HB-3 Fuel Section, Showing Thermocouples (7515-51180)	40
38. HB-4 Fuel Section and Top Boron Steel Section, Showing Thermocouples (7515-51331F)	41
39. Components for HB-4 (7515-51331B)	41
40. HB-4 Fuel Section (7515-51331C)	43
41. Complete HB-4 (7515-51331K)	43
42. Looking Through Fuel Section of HB-2, After Irradiation in OMRE (7519-51223-9)	44
43. Side View of Fuel Stack from HB-2, After Exposure in OMRE (7519-51225-11)	44
44. Typical Flat Plate from HB-2, After Exposure in OMRE (7519-51227-13)	44

ABSTRACT

Fuel elements for the Organic Moderated Reactor at Piqua, Ohio, (Piqua OMR) consist of 1.94% enriched U - 3.5 Mo - 0.1 Al alloy, nickel-bonded to extended surface Type 1100 aluminum cladding, in the form of two concentric circular cylinders.

The development program for these elements included:

- 1) The evaluation of fuel alloys having compositions near U - 3.5 Mo (with small ternary additions of Al and Si)
- 2) The casting of fuel cylinders
- 3) The preparation of helically-finned extruded cladding
- 4) The application of the nickel bond layer and bonding by hot pneumatic pressing
- 5) The establishing of procedures for fuel mechanical assembly.

The test program involved the irradiation of prototypes and out-of-pile testing of full-scale mockups.

Results show that such elements are capable of successful performance under Piqua OMR conditions.

I. INTRODUCTION

The Piqua OMR plant is designed to produce a net power of 11,400 kwe. The reactor consists of a heterogeneous arrangement of slightly enriched uranium alloy fuel, clad in and metallurgically bonded to aluminum, immersed in an organic medium which serves as moderator-reflector and coolant. Early in the development program for this reactor, a project was established to accomplish two major goals:

- a) To develop a fuel element which will be stable under irradiation to 3000 Mwd/MTU, average, at 850°F peak, and compatible with organic medium.
- b) To determine process and product specifications for fuel element fabrication.

Both have been successfully accomplished.

During the development of the fuel element for Piqua OMR, two basic designs were considered.¹ Initially, the design was a flat-plate extended-surface configuration, as shown in Figure 1. The final design includes two concentric, extended-surface tubes, as shown in Figure 2. Much of the development of the various processes required was done on the flat plate concept and, where possible, extrapolated to make the tubular shapes. Many of the individual process steps had to be changed and further developed to fabricate the tubular element. In this report, an attempt will be made to trace the development of the major process steps, including the necessary additional effort required by the change in shape.

The fuel element development project consisted of the following steps:

- a) Fuel alloy development, evaluation, and selection
- b) Melting and casting fuel alloy
- c) Cleaning and plating
- d) Bonding fuel to cladding
- e) Final assembly

Each of these will be discussed in detail in this report.

Figure 1. Eighty-Plate OMR Fuel Element

Figure 2. Tubular OMR Fuel Element

II. FUEL DEVELOPMENT, EVALUATION, AND SELECTION

This development program was guided by two design requirements:

- a) A fuel life expectancy of 5000 Mwd/MTU peak (3000 Mwd/MTU average)
- b) A fuel enrichment less than 2 wt % U^{235} .

Therefore, the following criteria were established:

- a) Fuel dimensional changes, under irradiation, should not exceed 5% change in volume per atom percent burnup, at a maximum central temperature of 850°F.
- b) The fuel alloy must withstand stresses induced by thermal cycling.
- c) The fuel should have sufficient strength and creep resistance to be mechanically stable at operating conditions.
- d) Alloying additions should not exceed 5 wt %, and should be of low absorption cross section, consistent with the limitation on enrichment.
- e) The process should lend itself to economic fabrication.

It was recognized that a complete evaluation of fuel alloy stability, under irradiation, could only be accomplished in the environment of an operating reactor. As facilities for such testing were very limited, time consuming, and expensive, an out-of-pile testing approach was attempted. The major emphasis was placed on developing an alloy which would resist plastic deformation at 850°F.¹ Resistance to plastic deformation requires a material of high creep resistance and yield strength at elevated temperatures. Consideration was also given to eliminating phase changes, with their attendant volume changes; or at least to minimize such changes. The development of such fuels, by alloying, is discussed completely in References 2 and 3. From these, we can draw the following conclusions:

- a) An alloying addition of 3.5 wt % Mo significantly increases the stability of as-cast uranium during thermal cycling. This addition eliminates the β phase; and, therefore, the α phase transforms to γ phase only.

- b) The addition of 3.5 wt % Mo increases the ultimate and yield strengths of as-cast uranium by a factor of five. The addition of 0.1 wt % Al to the binary further increases these properties, about seven times that of unalloyed uranium. An addition of 0.1 to 0.5 wt % Si did not improve the properties over those of the binary alloy.
- c) The creep strength of U is significantly increased by the addition of 3.5 wt % Mo. This improvement is enhanced by further addition of either aluminum or silicon (0.1 to 0.5 wt %). The U - 3.5 Mo - 0.1 Al^{*} showed the highest creep strength of all the low alloys tested. Table I shows results of tensile tests at 900°F, and Table II indicates creep tests at various temperatures and stress levels.² From the above data, three alloys were selected for in-pile evaluation, U - 3.5 Mo, U - 3.5 Mo - 0.5 Si and U - 3.5 Mo - 0.1 Al. All three have been irradiated, and the results are discussed in Section IX of this report.

*Figures denote weight percent

TABLE I

RESULTS OF TENSILE TESTS AT 900°F

Alloy	Specimen Number	Stress (10 ³ psi)				Elongation (% in 2 in.)
		Ultimate Strength	0.2% Yield Strength	0.1% Yield Strength	0.02% Yield Strength	
U - 3.5 Mo - 0.1 Al	354-4	114.7	75.3	62.8	43.3	1.5
	354-5	117.0	75.6	62.7	40.0	1.7
	354-6	98.5	90.8	69.0	45.1	1.0
	410-2	-	84.8	70.8	58.6	-
	410-3	-	70.2	56.4	34.6	-
	410-6	-	91.3	80.7	59.6	-
	Average	110.1	81.4	67.1	46.8	1.4
U - 3.5 Mo - 0.5 Si	300-1	74.7	55.0	44.6	30.2	0.6
	300-2	66.4	54.6	43.9	32.2	0.6
	339-5	79.5	65.0	57.5	39.8	1.5
	339-6	97.5	64.7	57.9	40.8	2.2
	Average	79.5	59.8	50.9	35.8	1.1
U - 3.5 Mo	338-1	79.0	40.8	31.6	15.7	11.0
	338-2	73.5	42.0	32.6	22.5	3.5
	338-5	99.0	73.0	62.0	41.9	2.5
	338-6	98.8	68.5	57.4	39.5	2.5
	372-2	99.2	70.0	63.5	53.2	2.0
	372-5	97.0	66.9	58.9	44.3	5.5
	372-6	92.0	61.7	53.4	41.1	6.2
	399-1	96.8	65.5	50.4	37.7	7.5
	399-2	95.2	67.4	59.8	46.8	7.5
	376-1	84.4	57.2	48.4	30.1	2.5
	Average	91.5	61.3	51.8	37.2	5.6
U - 3.5 Mo - 0.1 Si	353-5	79.3	53.4	39.6	20.4	0.5
	353-6	64.5	57.6	45.2	26.9	0.5
	Average	71.9	55.5	42.4	23.7	0.5
U - 3.5 Mo - 0.5 Al	305-1	52.6	-	-	52.6	0.2
	305-2	49.4	-	-	36.5	0.2
	305-6	53.6	-	-	46.8	0.2
	Average	51.8	-	-	45.3	0.2

TABLE II
RESULTS OF CREEP TESTS OF VARIOUS ALLOYS*

Alloy	Specimen Number	Test Temperature (°F)	Minimum Creep Rate (%/hr)							Duration of Tests (hr)
			Stress Level (psi x 10 ³)							
			10	15	20	30	40	45	50	
U - 3.5 Mo - 0.1 Al	354-1	900	0.0025	0.0025	0.004	-	-	-	-	218
	354-7	900	-	-	-	0.0032	0.0057	0.0084	0.026	648
	354-8	900	-	-	0.003	0.003	0.0065	-	†	355
	410-1	900	-	-	0.005	0.006	0.013	0.023 [†]	-	-
	410-1	800	-	-	0.001	-	-	-	-	-
		900	-	-	0.002	-	-	-	-	192
		1000	-	-	0.018	-	-	-	-	-
	410-5	800	-	-	-	0.0025	-	-	-	190
	900	-	-	-	0.007	-	-	-	-	
U - 3.5 Mo - 0.5 Al	305-1	900	0.003	0.003	0.003	-	-	-	-	599
U - 3.5 Mo - 0.5 Si	300-1	900	-	0.0038	0.0043	-	0.0045	-	-	426
	300-2	900	-	-	0.004	-	0.0048	-	-	460
	339-4	900	-	-	0.0055	-	0.012	0.027	-	-
	339-5	900	-	-	-	-	-	0.0076	0.021	164
U - 3.5 Mo	338-3	900	0.0054	-	0.013	-	-	-	-	164
	365-1	900	-	-	0.012	0.023	-	-	-	233
	365-2	900	-	0.009	-	-	0.033	-	-	-
	372-4	900	-	-	0.007	-	-	-	-	137
		1000	-	-	0.175	-	-	-	-	22
	372-3	900	-	-	-	-	-	0.037	-	54
	372-1	900	-	-	-	-	-	-	0.166	24
	-	900	-	0.007	-	-	-	-	-	-

*Sheet specimens, machined from as-cast plates
†Ruptured at indicated stress

III. MELTING AND CASTING

The shaping of enriched uranium alloys by casting eliminates extra costs that are often associated with recovery of the expensive U^{235} in nonrecyclable scrap, when these alloys are shaped by wrought methods. Another reason for choosing a casting process was the necessity, in the Piqua OMR fuel design, of making a large number of relatively short-length pieces. The process, which is described in Reference 4, essentially consists of vacuum induction melting uranium derby, molybdenum pellets, and other alloying additions, and casting into warm, magnesium-zirconate-coated graphite molds. The casting of flat plates, 0.130 in. thick, 2-1/2 in. wide, and 14-in. long, was accomplished in a 12-cavity mold. The resultant cast plates are shown in Figure 3. Proper outgassing of all components during the melting cycle was required, to insure good surface appearance and sound metal with a minimum of internal porosity.

Figure 3. Typical Uranium Alloy OMR Fuel Plates
Cast to Thickness

Figure 4. Top of Mold for
Casting Six Cylinders
of U - 3.5 Mo Alloy

Figure 5. Mold for Casting
Tubular Sections,
Showing Graphite
Cores

The casting of the tubular sections involved several modifications of this process. The sizes required were approximately 5-in. OD and 0.2-in. thick wall, and 4-in. OD and 0.2-in. thick wall. The mold temperature was a much more important variable in controlling surface and internal porosity. In addition, it was necessary to outgas all graphite components, as a separate operation, before casting and induction heating. With these special precautions added, the resultant castings were sound and had good surface appearance. Six castings were made simultaneously, as shown in Figures 4 and 5. The eight as-cast tubular sections shown in Figure 6 are sufficient for one element. Six sections were cast simultaneously in a duplex mold.

Figure 6. Eight Castings for Tubular Element

The flat plate sections were machined only on four edges, to cut to length and width. The tubular sections had to be machined on ID and OD, to obtain the required tolerance of ± 0.003 in. on wall thickness and maintain their ovality.

Radiographic and density tests have shown that the as-cast material is sound. Chemical compositional control was adequate, and the molybdenum was held to $\pm 0.3\%$. Carbon pickup was no problem; maximum carbon content in as-cast bodies was in the range of 800 ppm.

IV. NICKEL PLATING AND CLADDING

After the flat plate fuel cores were machined, they were handled in the following manner.⁵ The plates were cleaned by blasting with 50-mesh chilled steel grit. Previous attempts, using Alundum grit, resulted in entrapped particles on the fuel plate surface. Nickel was electrodeposited on the as-blasted plate surfaces, using a specially designed rack which permitted changing contact points without interrupting the current (Figure 7). Table III details the plating steps required.

Figure 7. Plating Rack for Flat Plate - Movable Contact Type

TABLE III
NICKEL-PLATING PROCEDURES FOR FLAT PLATES

1. <u>Degrease</u>	Trichloroethylene vapor
2. <u>Sandblast</u>	50-mesh chilled steel grit. Air pressure, 80 to 100 psi
3. <u>Alkaline Anodic Etch</u>	
Bath Composition	10 to 12 oz/gal. "Oakite 160" (proprietary material of Oakite Products, Inc.) in water
Temperature	60 to 70°C
Time	1 to 2 min, or until surfaces display uniform golden brown iridescence
Current	20 amp/ft ² of anode area
Cathode	Mild steel tank
4. <u>Tap Water Rinse</u>	Momentary immersion in flowing water
5. <u>Nitric Acid Etch</u>	
Composition	20 to 50 vol % of 38° Bé nitric acid in water
Temperature	Ambient
Time	3 to 5 min, or until surfaces display bright metallic lustre
6. <u>Tap Water Rinse</u>	Momentary immersion in flowing water
7. <u>Neutralizing Rinse</u>	
Composition	Tap water saturated with NaHCO ₃
Time	Momentary immersion in static bath
Temperature	Ambient
8. <u>Distilled Water Rinse</u>	Immersion plus ambient temperature spray rinse
9. <u>Electroplating</u>	
Bath composition	NiSO ₄ · 7H ₂ O 240 g/l NiCl ₂ · 6H ₂ O 45 g/l H ₃ BO ₃ 30 g/l Distilled H ₂ O solution
Strike	None, cathode enters bath with current on
Current	50 amp/ft ² of cathode area
Anodes	Rolled, depolarized nickel, bagged in nylon cloth
Temperature	40 to 55°C
pH	3 to 5.5 (electrometric)
Time	12 min, deposits 0.5 mil/surface
Agitation	Argon gas, 0.2 ft ³ /min-liter of solution
Anti-pitting agent	H ₂ O ₂ , as required

Several aluminum alloys were considered for the cladding. As the cladding which is metallurgically bonded to the fuel material in this element acts only as an envelope to retain fission products and prevent contamination of coolant, it was decided that Type 1100 aluminum would perform satisfactory. The uranium alloy is the structural member of the fuel element. Further tests, described later, confirmed this.

The Type 2S aluminum cladding, shown in Figure 8, was prepared by extruding, sawing to length, and degreasing. It was then etched in 5 wt % NaOH bath, cleaned in 6 to 8 Normal nitric acid, rinsed thoroughly in distilled water followed by methanol, and dried by blotting with tissues.

The nickel-plated core was then slid very carefully into the cleaned cladding, one end of which had been closed by a fusion-welded plug. The other end of the cladding was closed by a hot knifing procedure. It was necessary to weld a tube to one end plug for outgassing before pressing. Hot knifing apparatus is shown in Figure 9. The various components before assembly are shown in Figure 10. After the fuel was sealed within the cladding, the assembled plate was outgassed at 1000°F for several hours. The evacuation tube was then hot knifed to seal the entire assembly, thereby producing an evacuated, sealed assembly, ready for hot pressing.

The tubular fuel sections were handled in a slightly different manner.⁶ The as-cast hollow cylinders were end cropped and machined to tolerances on OD and ID. The machined tubular sections were degreased, degassed in vacuum for a minimum of 12 hr, grit blasted, washed in methyl alcohol, and weighed. The cylinder was then ready for nickel plating. The plating rack, designed specifically for this shape, is shown in Figure 11. The nickel plating procedure is detailed in Table IV.

The aluminum cladding, shown in Figure 12, and all aluminum components were degreased in trichlorethylene vapor. The aluminum components were cleaned as shown in Table V.

Figure 8. Flat Plate Aluminum Cladding

Figure 9. Hot-Knifing Apparatus

Figure 10. Components of Flat Plate Fuel Section

TABLE IV

NICKEL PLATING PROCEDURES FOR U - 3.5 Mo
CYLINDRICAL CORES

Figure 11. Plating
Rack for Tubular
Fuel Cores -
Movable
Contact
Type

1. <u>Degrease</u>	Trichloroethylene vapor and liquid
2. <u>Grit Blast</u>	50-mesh chilled steel grit: Air pressure, 8 to 100 psi (dry, filtered)
3. <u>Tap Water Rinse</u>	Pressure spray all surfaces at ambient temperatures
4. <u>Distilled Water Rinse</u>	Pressure spray all surfaces at ambient temperatures
5. <u>Electroplate</u>	
Bath composition	$\text{NiSO}_4 \cdot 7\text{H}_2\text{O}$ 40 oz/gal $\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$ 4 oz/gal H_3BO_3 4.5 oz/gal Distilled water solution
Strike	None. Cathode enters bath with current on
Current	50 amp/ft ² of cathode area
Anodes	Tank - rolled depolarized nickel, bagged in nylon cloth Internal - 3-in.diameter com- mercial platinum or graphite
Temperature	40 to 55°C
pH	3.8 to 4.2
Time	Plate for 12 min, change contacts, plate for additional 12 min to deposit total of 1.0 mil
Agitation	Argon gas, 0.2 ft ³ /min-liter of solution
Antipit Agent	H ₂ O ₂ additions, as required
6. <u>Tap Water Rinse</u>	Pressure spray at ambient temperature
7. <u>Distilled Water Rinse</u>	Pressure spray at ambient temperature
8. <u>Dry</u>	Blot with clean, lint-free tissue

Figure 12. Tubular Aluminum Cladding

Figure 13. Components of Tubular Fuel Section

TABLE V

TUBULAR ALUMINUM CLADDING SURFACE PREPARATION

1. <u>Degrease</u>	Trichlorethylene vapor and liquid
2. <u>Alkaline Etch</u>	
Bath Composition	12 oz/gal of "Oakite 160" (proprietary material of Oakite Products, Inc.) in water
Temperature	60 to 70°C
Time	1 min
3. <u>Tap Water Rinse</u>	Momentary immersion
4. <u>Nitric Acid Clean</u>	
Bath Composition	6 to 8 Normal nitric acid
Temperature	Ambient
Time	1 to 2 min
5. <u>Tap Water Rinse</u>	Momentary immersion
6. <u>Distilled Water Rinse</u>	Pressure spray
7. <u>Air Dry</u>	

The fuel section was assembled as follows:

- a) One end plug was positioned on a table.
- b) The nickel plated fuel cylinder was placed, upright, on the end plug.
- c) The inner cladding was slipped into position.
- d) The other end plug was positioned over the inner cladding.
- e) The outer cladding tube was positioned over the end plugs and fuel cylinder.
- f) The evacuation tube was positioned in the prepared hole.

An exploded view is shown in Figure 13.

The end closures and evacuation tube welds were made with the use of water cooled chill blocks on the ID and OD of the cladding. A normal Heliarc welding cycle was used, in conjunction with a controlled rotary welding fixture. After welding, the assembly was helium leak checked and evacuated, at room temperature and then at 1000°F, to below 50 μ . Following hot knifing of the aluminum evacuation tube, the fuel section was ready for hot pressure bonding (Figures 14 and 15).

Figure 14. End View of Welded End Plug and Sealed Off Evacuation Tube for Tubular Sections

Figure 15. Hot Pressed Tubular Sections

V. HOT PRESSURE BONDING

Heat transfer studies indicated the necessity for a metallurgical bond between the uranium alloy core and the aluminum cladding. The solid-state diffusion of these two metals is so rapid, at the Piqua OMR operating temperatures, that it was necessary to include an antidiffusion barrier which would bond to both the cladding and the core. After investigating several materials, such as copper, silver, and nickel, for such a barrier layer, nickel was selected because of its low cross section, ease of application, and high melting point. It was believed that, because of its high melting point, nickel would diffuse slower and therefore increase the life of the bond at elevated temperatures.

The three variables, time, temperature, and pressure, which had to be determined for this operation, were established, using small specimens.⁵ The first attempts were made in steel dies; but, because of the redesign of the element to include the extended surface, pneumatic methods were developed, using helium or argon as the pressurizing fluid. After conducting many tests, the conditions selected for flat plates were 4 tsi at 1000°F for 15 min. The prepared plate assemblies were isostatically pressed in a thick-walled vessel whose inside dimensions were 3-1/16-in. diameter and 20 in. deep. A resistance-wound clam shell heater, of 4 kw capacity, surrounded the vessel. After this procedure had been developed, approximately 500 plates were hot pressed in this equipment.

It was initially thought that the process could be extrapolated from the flat plate to the larger tubular components with little or no development work. However, many modifications and detail improvements had to be made, in order to adapt the process effectively to the new shapes.

To insure a sound weld joint, prior to hot pressing, considerable care had to be taken with the end plug design. The design shown in Figure 15, which was the one finally chosen, permitted the isolation of leaks in weld areas, isolated the evacuation tube weldment from end plug welds, removed the restriction on evacuation tube size, greatly simplified repairs to welds, and eliminated rejects due to end closure welds. Figure 16 shows the component and the welded assembly with the evacuation tube welded in position.

Figure 16. Components of Tubular Section,
Showing Evacuation Tube Welded to End Plug

Figure 17. Water Cooled Copper
Chill Blocks for Welding
Tubular End Closures

Another problem, which was not evident with flat plates, was the effect that the welding of end plugs had on the other components. The amount of heat generated, during the welding cycle with tubular fuel, oxidized the nickel-plated uranium to an extent which prevented complete diffusion during subsequent hot pressing. A water cooled copper chill block had to be designed; its use successfully prevented the cladding from reaching a temperature higher than 150°F. Figure 17 depicts such an arrangement.

Because the mass of the cylindrical sections was approximately 10 times that of the flat plates, it soon became evident that it would be necessary to outgas the individual cast sections, to remove the dissolved and absorbed gases. An outgassing cycle, of 16 hr at 1050°F in a vacuum of 5μ or less, was satisfactory; but an optimum cycle was not determined.

Hot isostatic bonding of tubular sections required a much larger and complex facility than previously reported.⁵ The pressure vessel was 6 in. ID, 18 in. effective depth, and was rated at 15000 psi at 1000°F. The gas compressor was rated at 10,000 psi for continuous delivery of argon. The furnace for heating was an air circulatory type, rated at 33 kw.

After completion of many other minor modifications, which are detailed in Reference 6, the tubular sections were successfully and repeatedly hot pressure bonded (Figure 15).

VI. BOND EVALUATION AND TESTING

The Al-Ni-U system has been studied at many different sites. A good summary of the work is given in Reference 7.

During the development of the flat plate element, a 0.001-in. thick nickel deposit was applied to all surfaces. A typical diffusion bond zone which resulted after hot pressing is shown in Figure 18. The aluminum end plugs were also nickel plated, as it was thought that dissimilar metals would promote better bonding. Figure 19 shows a typical bond area in the aluminum end plug-to-cladding region.

While developing the hot pressing techniques for the tubular element, several minor changes were included to improve the bonding. An alternate cleaning cycle was attempted, which used a nitric-hydrofluoric acid combination, in place of nitric acid, but this turned out to have many disadvantages. Finally, it was decided to nickel plate directly onto a steel-grit blasted surface. Figure 18 shows the resulting Al-Ni-U interface. Good bonding was confirmed by chisel peel tests and metallographic examination. For aluminum end plug-to-cladding bonds to be obtained without a nickel layer, it was found that proper surface preparation permitted good bonding. Table VI enumerates steps for good surface preparation of Type 6061 aluminum. A typical photomicrograph of Type 1100 cladding to Type 6061 end plug is shown in Figure 20.

The testing of the metallurgical bond is a prerequisite for good quality control. Procedures used included metallographic examination, peel test, and macro etching. No satisfactory nondestructive test is known for evaluation of the bond with the particular geometry present here. Most nondestructive tests measure the change in thickness of materials; and, because of the extended surface, the thickness of the bonded section is quite variable. Ultrasonic, eddy current, sonic, and infrared methods were tried. Preliminary evaluation indicated that the most promising of these is the transient-heating infrared scanning procedure, but more development is required to establish it as an entirely reliable test.

Etchant: $\text{NaCN}, (\text{NH}_4)_2\text{S}_2\text{O}_8$
BF Light

500 X

Figure 18. Typical Al-Ni-U Diffusion Bond Zone, Isostatically Pressed at 1000°F and 8000 psi for 10 min

Unetched
BF Light

250 X

Figure 19. Typical Bond Zone, End Plug Nickel Plated to Cladding

Etchant: 10% NaOH
BF Light

250 X

Figure 20. Bond Zone of Hot Pressed Type 6061 End Plug to Type 1100 Cladding

TABLE VI

TYPE 6061 ALUMINUM END PLUG SURFACE PREPARATION

1. <u>Degrease</u>	Trichloroethylene vapor and spray
2. <u>Alkaline Etch</u>	
Bath Composition	12 oz/gal of "Oakite 160" (proprietary material of Oakite Products, Inc.) in water
Temperature	60 to 70°C
Time	1 min
3. <u>Tap Water Rinse</u>	Immersion with agitation
4. <u>Desmut</u>	
Bath Composition	50 vol % Hydrochloric Acid
Temperature	Ambient
Time	15 to 30 sec
5. <u>Tap Water Rinse</u>	Immersion with agitation
6. <u>Nitric Acid Clean</u>	
Bath Composition	6 to 8 Normal nitric acid
Temperature	Ambient
Time	1 to 2 min
7. <u>Tap Water Rinse</u>	Immersion with agitation
8. <u>Distilled Water Rinse</u>	Immersion with agitation, followed by pressure spray
9. <u>Air Dry</u>	Oil-free, filtered air under pressure

Figure 21. Eighty Plates, Assembled for Full-Size Flat Plate Element

Figure 22. Complete Flat Plate Element

VII. FINAL ASSEMBLY

After the hot pressed components were inspected, the fuel element was assembled. This step was accomplished with very little development work required. During the process development, several full-size mockup elements were made, of both flat plate and tubular sections.

The flat plate element consisted of 80 fuel sections which were assembled into 4 bundles of 20 plates each.

The assembly sequence for the flat plate element was:

- a) Place 2 fuel-plate stacks, of 10 plates each, 2 plates wide, on a flat surface.
- b) Affix a pair of parallel clamps at each end of the fuel section.
Tighten the clamps until all fuel plate spacers are in intimate contact.
- c) Place the fuel section on end and affix stainless steel retaining clips to the middle and outer aluminum fuel plate spacers. Use special staking pliers to secure the clips to the aluminum spacers. (Figure 21 shows such an arrangement.)
- d) Repeat operation (c) on the opposite end of the fuel section, for all 4 fuel bundles.
- e) The subassemblies (20-plate bundles) are slid into a stainless steel outer box. The 4 subassemblies are stacked and assembled, with tongue and groove, to their predetermined position.
- f) The head extension, outer box, and lower plug are assembled in a welding jig, and junctions between the components are welded.
- g) The finished element is measured for Total Indicated Reading (TIR) and length, and the welds are nondestructively examined. Figure 22 shows a completed element.

The assembly procedure for the tubular element was:

- a) Place the lower plug in an upright position
- b) Place the inner stainless steel can, upright, in its seat in the lower plug.

Figure 23. Tubular Sections,
Assembled for Full-Size
Element

Figure 24. Complete Full-Size
Tubular Element

- c) Position the inner fuel sections on the inner sleeve (The bottom section rests on its seat in the lower plug).
- d) Position the outer fuel section concentric with the inner section, and seat it on the lower plug.
- e) Position the second inner section around the inner can and seat it on the bottom fuel section.
- f) Position the second outer section on the bottom outer section.
- g) Repeat these operations until all eight sections are loaded. Figure 23 shows the stacked fuel sections.
- h) Position the outer stainless steel can around the fuel stacks and seat it on the lower plug.
- i) Position the upper plug, with its premachined seat resting on the ID of the outer can.
- j) Place the assembly in a welding jig, and join all components by welding.
- k) Measure the finished element for TIR and length, and nondestructively examine all welds. The completed element is shown in Figure 24.

One of the major differences in design between flat plate and tubular elements was the addition, to the latter, of a variable orifice to control coolant flow. This and the locking mechanism, screen, and support bars are prefabricated and assembled, prior to final assembly.

VIII. OUT-OF-PILE TESTING

A full-size mockup element of each design, made by the process developed and described previously, was tested in an organic loop. The fuel alloy was made with depleted uranium; but, in all other respects, these elements met design requirements for actual core elements.

The flat plate design consisted of 80 plates, in 4 bundles of 20 each, as shown in Figure 21. The completed element is shown in Figure 22.

The test was run in Santowax OM at 750°F for 345 hr. Then the temperature was raised to 800°F for 718 hr.⁷ During this test, the flow indications did not change and remained at a constant velocity of 15 fps. It was concluded that the aluminum end plugs and cladding did not creep at these conditions. Figure 25 shows these plates, after exposure to test; and Figure 26 shows the partially decanned element, after testing.

Figure 25. Three Plates, After Exposure in Organic Loop at 800°F

Figure 26. Partially Decanned Flat Plate Element, After Exposure in Organic Loop at 800°F

The environmental testing of the full-size tubular element mockup was done in the same organic loop as previously described. The test conditions were as follows:

- a) Variable orifice full open
- b) Santowax OM at 730°F
- c) Average pressure drop - 27 psi
- d) Organic flow - 230 gpm
- e) Duration of test - 40 hr

The element was cooled, and the orifice manipulation was checked. The loop was then operated at the following test conditions:

- a) Variable orifice completely closed
- b) Santowax OM at 750°F
- c) Average pressure drop - 28 psi
- d) Organic flow - 100 gpm
- e) Duration of test - 67.5 hr

The fuel components, as assembled, are shown in Figure 23; and, as a completed element, in Figure 24. After the element was removed from the test vessel, it was noted that severe deformation of the outer can had taken place. The deformation of the outer 0.020-in. thick, Type 304 stainless steel can, shown in Figure 27, was caused by flow conditions in the loop, which placed an

Figure 27. Tubular Element, After Exposure in Organic Loop at 750°F

Figure 28. Partially Decanned Tubular Element, After Exposure in Organic Loop at 750°F

external pressure on the element. The loop had been designed and built to specifications for the flat plate element, for which an external pressure on the outer can of the element is a proper design condition. The tubular element was designed to have an internal pressure, at all times, which would prevent any such buckling. Another test is scheduled, in a modified loop, and will be reported separately. An interesting fact was uncovered from this test. After the fuel sections were decanned, it was noted that the fins were not damaged and that the coolant channels remained open and complete. This substantiated the flow readings, which indicated no change in flow throughout the test, although the outer can collapsed. The partially decanned fuel element is shown in Figure 28.

It was shown, from these out-of-pile tests, that the elements are structurally sound. The aluminum extended surface cladding showed no tendency to creep and performed exceedingly well, even under adverse conditions. In addition, it was proved that the variable orifice adequately controls the flow and can be manipulated, after operating at high temperatures in an organic medium.

Figure 29. Fuel Sections and Boron Steel Section for HB-1

Figure 30. Two Bundles of Fuel, Showing Thermocouple Arrangement for HT-1

IX. IN-PILE TESTING

During the development of the Piqua OMR element, five prototype elements were made and inserted into OMRE for irradiation proof testing. In July, 1958, two elements, designated HB-1 and HT-1,⁸ were inserted. HB-1 was fabricated from flat plates consisting of three plates of 8 wt % enriched U - 3.5 wt % Mo alloy and two plates of U - 3.5 wt % Mo - 0.5 wt % Si alloy, alternately spaced, as shown in Figure 29. The top and bottom sections, which completed the element, were made from 1 wt % boron Type 304 stainless steel (which are also shown in Figure 29), to match neutron absorption along the length of the assembly. The plates were cast, plated, and bonded, as described in previous sections. The assembly of a 5-plate fuel section consisted of simply stacking the components on top of each other and fastening the group together by means of a Type 304 stainless steel clip which fitted over the four corners of the bundle. This assured a rigid configuration for subsequent handling.⁸ The thermocouples were situated in a premachined groove in the spacer of the fuel plate cladding. Typical thermocouple installation and location is shown in Figure 30 (although this is for the HT-1 element).

The HT-1 element was identical to HB-1, except that all three bundles contained fuel, and the enrichment was 4 wt %. The top and bottom bundles, of five plates each, contained U - 3.5 Mo, while the center section contained U - 3.5 Mo - 0.5 Si alloy plates. The top and center sections are shown in Figure 31. A "hot-wire" anemometer was installed, to measure coolant flow. This consisted of a nickel wire, of known electrical resistance, wrapped around an insulator. It operated by measuring the variations in resistance with changes in temperature caused by flow changes. The final assembled element, showing anemometer connection and location, is shown in Figure 32.

These two elements operated in OMRE for approximately four months. At this time, a steady increase of outlet and surface temperature readings, with a corresponding decrease in flow, was noted; and the elements were removed for hot cell examination. After the end fittings were removed, it was quite obvious what had caused the elements to fail. Figure 33 shows how the inlet end of the coolant channels of the fuel section from HB-1 was completely blocked by solid

Figure 31. End View of HT-1

Figure 32. Complete Element, Typical of HB-1, HB-2, and HB-3

Figure 33. Bottom End of Fuel Stack of HB-1, After Removal from OMRE

Figure 34. HB-1, After Irradiation, Showing Molten Cladding

materials which were filtered out of the coolant stream by this element. After the plates were separated, it was also noted that some melting of cladding had occurred, which was caused by overheating after the coolant channels were blocked. Figure 34 shows a chunk of aluminum which had apparently melted, oozed out between the fuel plates, and frozen on the cooler boron-steel plates.

The results of hot cell examination of HT-1 were essentially the same. No melting was observed, but a blistered area was found on one plate, which was attributed to local overheating.

Several of the plates were measured, and the results were compared with preirradiation data.

	<u>Mean Thickness (in.)</u>	<u>Mean Width (in.)</u>	<u>Mean Length (in.)</u>
Original Dimension	0.470	2.380	12.175
HB-1 Element (U- 3.5 Mo) Plate	0.469	2.382	12.245
Change	-0.001	+0.002	+0.070
HT-1 Element (U - 3.5 Mo - 0.5 Si) Plate	0.474	2.384	12.259
Change	+0.004	+0.004	+0.084

These measurements were taken across the aluminum surfaces; and some uncertainty arises, due to a slight surface coating of the plates.

Metallographic examination was done on several plates from each element. The Al-Ni-U bond was still intact, except where fuel plates were definitely overheated.

The following conclusions were formulated, from the examination of HB-1 and HT-1:⁸

- a) Both elements were damaged by coolant flow restriction, caused by the blocking of coolant channel entrances by external matter.
- b) HB-1 showed signs of aluminum melting, in certain areas, while adjacent areas still were structurally and metallurgically sound.

- c) Dimensional change data showed an increase only in length (0.6 to 0.7%) which may or may not be significant. Therefore, both compositions appear to be stable, up to 2300 Mwd/MTU,³ the peak burnup attained.

After these two elements were evaluated, it was decided that another in-pile test was required, to prove the applicability of the design and materials. In addition, at about this time, the design was changed from the flat plate to the tubular shape; and the U - 3.5 wt % Mo - 0.1 wt % Al alloy was selected as the reference fuel composition, because of its extremely high creep strength. Three elements, HB-2, HB-3, and HB-4, were fabricated and inserted into OMRE in July, 1959.

HB-2 essentially was a duplication of HB-1, with certain modifications. To decrease the probability of coolant channels being blocked, the fins were "blended" with a radius to eliminate all sharp corners. Figure 35 shows this feature, and also the thermocouple arrangement. It should be noted that each coolant channel temperature is monitored; and, in addition, another thermocouple measures the coolant ΔT between inlet and outlet temperatures. The length of the boron steel section was reduced from 12 to 4 in., as shown in Figure 36. To further insure that the blocking of coolant channels would not cause a failure of the element, a screen was placed inside the bottom end fittings of all three elements. The fuel alloy chosen for all sections of all three elements was U - 3.5 wt % Mo - 0.1 wt % Al. The enrichment of the uranium was 8 wt %.

HB-3 was fabricated exactly like HB-2, except that the fins were reduced 0.050 in., which created a 0.100-in. wide coolant channel between the fin tips. Figure 37 shows the bundle of fuel plates and the thermocouple arrangements, which are identical to those for HB-2.

HB-4 consisted of a single tubular fuel section, clad in extended-surface aluminum, approximating the shape of the Piqua OMR elements.⁸ The fuel was enriched to 5.7 wt %, and was instrumented with three surface thermocouples (Figure 38) and a thermocouple to measure the inlet and outlet temperature differential. The fuel cylinder was cast and machined to 2.540-in. OD and 2.240-in. ID. The processing, from machining fuel to finished bonded section,

Figure 35. HB-2 Fuel Section

Figure 36. HB-2 Fuel Section Plus Boron Steel Sections, Showing Thermocouple Arrangement

Figure 37. HB-3 Fuel Section, Showing Thermocouples

Figure 38. HB-4 Fuel Section and Top Boron Steel Section, Showing Thermocouples

Figure 39. Components for HB-4

was performed as previously described. The various components required for final assembly are shown in Figure 39. A closeup of the machined hot pressed fuel section, with holes for thermocouples, is shown in Figure 40. A complete description of the assembly process is included in Reference 9. The completed assembly is shown in Figure 41.

One element, HB-2, was removed from OMRE in April, 1960, for examination and evaluation, after about nine months in the reactor. There was no evidence of malfunctioning or failure of any component of HB-2 during the exposure. The estimated peak burnup was 4000 Mwd/MTU. The element, after the end adapters were removed, was found to be clean of any foreign debris. Figure 42 shows the coolant inlet end, in the foreground, with illumination at the other end of the bundle of plates. The coolant passages appear quite clean, with a slight warp evident in the top plate. Figure 43, of the bundle of plates, shows a side view of the one bowed outer plate. After the plates were separated, the individual plates were examined. A typical plate is shown in Figure 44. The clean surfaces and unaffected fin configuration are notable. Preliminary examination of the element showed no evidence of any failure. One plate, the highest burnup plate, showed definite "dishing", in one area; and, when measured, was thinner and longer than the other plates. The other four plates showed no indication of any changes from preirradiation conditions. Even in the one distorted plate, there was no damage to the cladding or the end plug bond, and no apparent change in fin configuration.

The element is presently being examined metallographically for bond and fuel alloy structure evaluation. Burnup will be determined, by gamma scanning and chemical analysis. Also, complete dimensional measurements will be made, for comparison with preirradiation values. The results of this examination will be reported separately.

The other two elements, HB-3 and HB-4, will remain in OMRE for longer burnups, in an attempt to establish the upper limit of usefulness of such elements.

Figure 40. HB-4 Fuel Section

Figure 41. Complete HB-4

Figure 42. Looking Through Fuel Section of HB-2, After Irradiation in OMRE

Figure 43. Side View of Fuel Stack from HB-2, After Exposure in OMRE

Figure 44. Typical Flat Plate from HB-2, After Exposure in OMRE

X. CONCLUSIONS

The development program for the Piqua fuel element is essentially complete. Through this work, it has been determined that ternary alloys, based on U - 3.5 Mo, can be cast into thin sections, and are stable under the operating conditions for the Piqua reactor. Aluminum is a suitable cladding material for such alloys, for use at temperatures of 750°F in organic media. A process has been developed and tested for the fabrication of an extended-surface tubular fuel element, which is an advanced element design. Hot isostatic pressing has proved successful for the metallurgical bonding of the components for such elements, and the use of infrared techniques has shown the greatest promise for the nondestructive testing of these bonds.

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