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FABRICATION OF URANIUM ALLOY FUEL ELEMENTS FOR OMRE FOURTH CORE

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ABSTRACT

The fuel elements for the fourth core loading of the Organic Moderated Reactor Experiment (OMRE) consist of nickel plated U-Mo alloy fuel, isostatically bonded to Type 1100 aluminum cladding. The fuel elements are flat-plate elements, with 18 fuel plates per element. Thirty-four Core IV fuel elements were fabricated. Twenty standard driver elements and five instrumented driver elements were made of U - 3.8 Mo - 0.2 Al. Three test elements each of U - 3.8 Mo - 0.2 Al, U - 7.5 Mo, and U - 10 Mo, for a total of nine test elements, were also made. All fabrication techniques used in this program were in accordance with the nuclear safety criteria outlined in Report NAA-SR-Memo 7001.

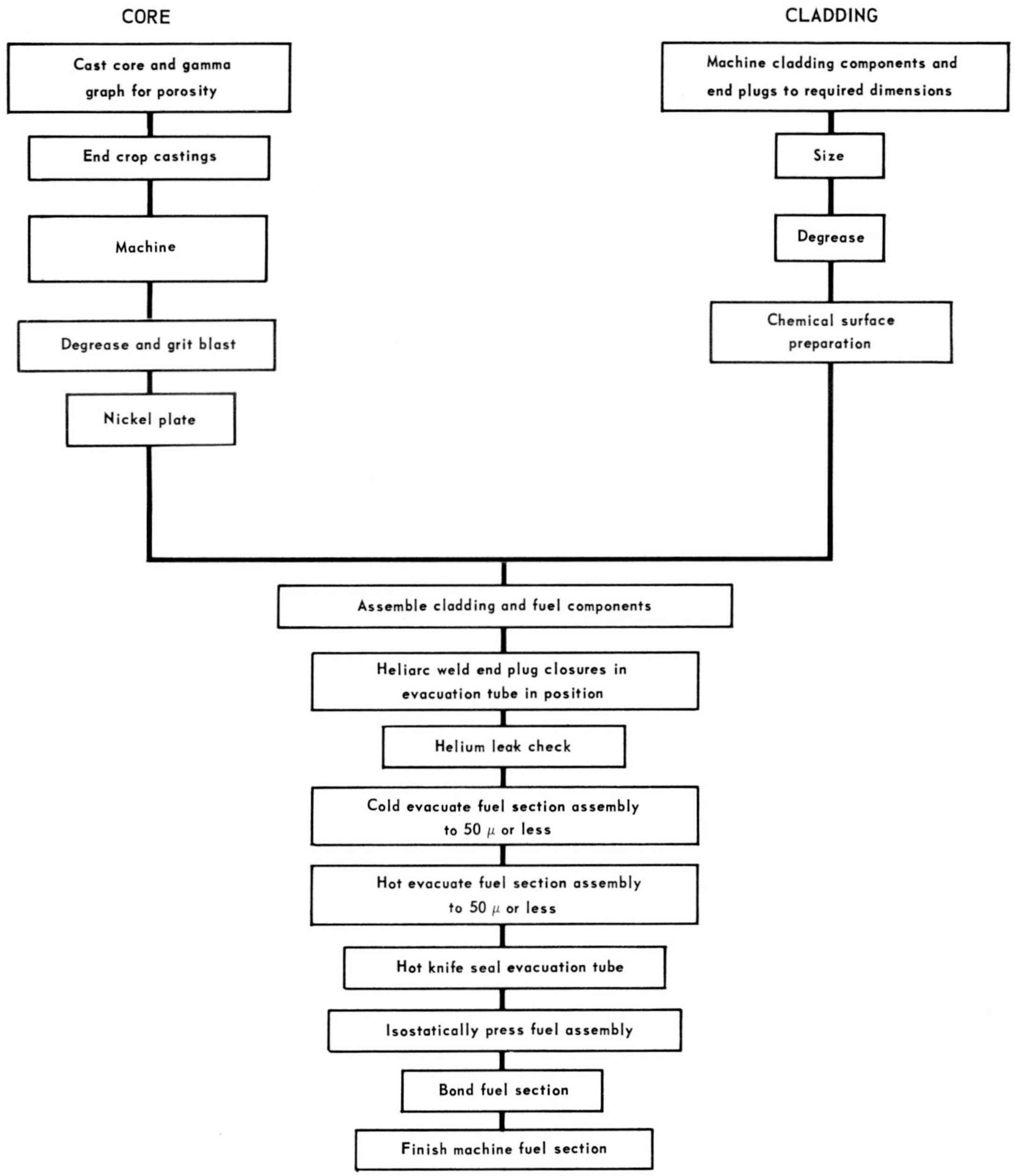

Figure 1. Process Flow Diagram for Fuel Plate Fabrication

I. INTRODUCTION

The Organic Moderated Reactor Experiment (OMRE) was initiated as a joint venture by Atomics International and the Atomic Energy Commission. The reactor was designed to obtain information about various performance parameters of organic moderator-coolant and fuel element concepts. The fourth core loading of the reactor consists of slightly enriched uranium alloy fuel, clad in and metallurgically bonded to aluminum. The organic coolant serves as a moderator and reflector.

This program was initiated to fabricate 34 fuel elements for the fourth core loading of the OMRE. Much of the development of the various processes required in the fabrication of this type of fuel element was done and reported earlier.[3-5] This report describes the processes used in fabricating the fourth core elements. The program consisted of the following phases:

a) Melting and casting the fuel alloy

b) Cleaning and plating the fuel cores

c) Bonding the fuel to the cladding

d) Final assembly and inspection.

Figure 1 outlines this fabrication process.

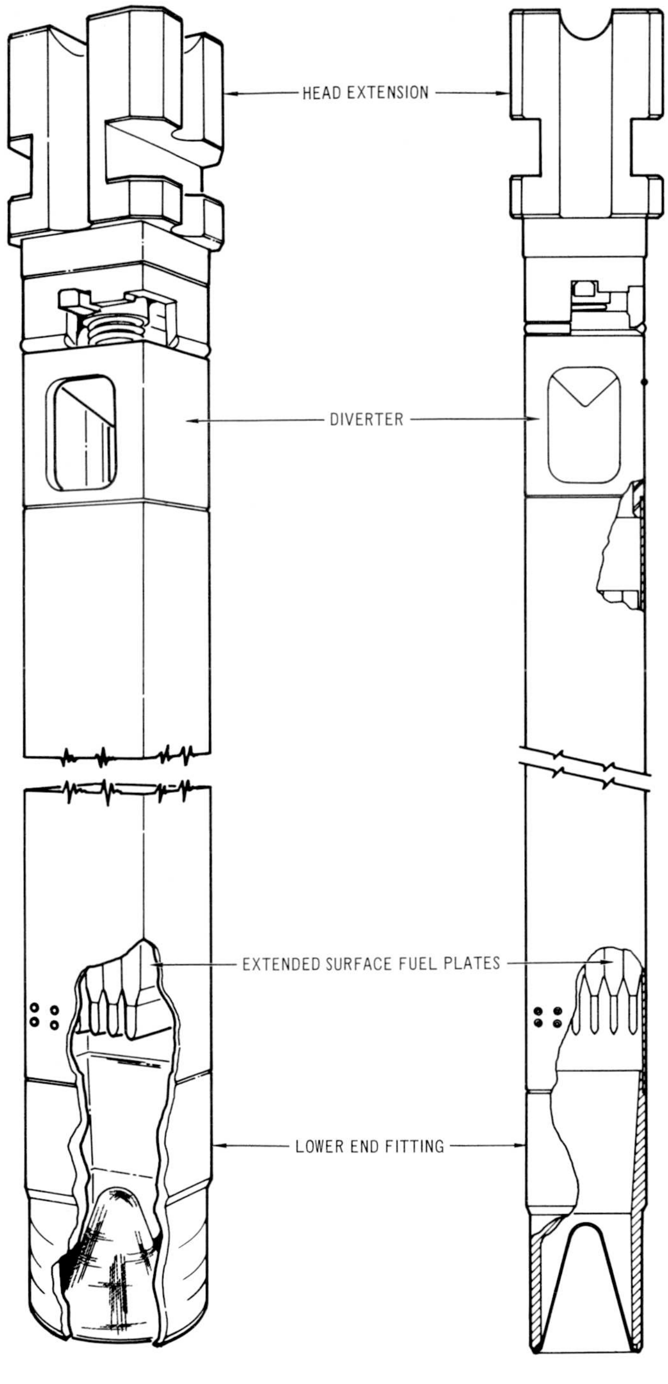

Figure 2. Eighteen-Plate OMRE Core IV Fuel Element

II. FUEL ELEMENT DESCRIPTION

The OMRE fourth core fuel element consists of 18 aluminum clad, slightly enriched (6.04%) uranium alloy fuel plates, arranged in a stainless steel box (See Figure 2). Castings are welded to each end of the fuel box, to direct the flow of coolant and to enable the fuel element to be installed in the reactor grid plates. The casting attached to the upper end of the fuel element serves to divert the flow of the coolant from the fuel element to the upper plenum chamber of the reactor. A casting welded to the diverter aligns the fuel element in the upper grid plate of the reactor, and contains a latching mechanism which locks the element into the upper grid plate. The actuating shaft of the latch mechanism also attaches to a tool which is used to install and remove the element from the reactor. A hollow casting, welded to the bottom of the fuel box, fits into the lower grid plate. This casting aligns the fuel element vertically, and permits the coolant to enter the lower end of the element.

OMRE FUEL ELEMENT DESIGN FEATURES

Final machined dimensions of clad fuel plate - 12.75 by 0.464 by 2.742 in.

Cladding material - Extended surface Type 1100 Aluminum

Fuel alloy - U - 3.8 Mo - 0.20 Al*

U - 7.5 Mo

U - 10 Mo

Uranium enrichment - 6.04%

Element assembly type - Box

Number of fuel plates per assembly - 18

Fuel box - 42 in. long, 2.850 in. square ID, with 0.050 in. wall, of Type 347 stainless steel

*Weight percentages

III. CASTING

Prior to this core loading, metal alloy fuel plates, 0.13 in. thick by 2-1/2 in. wide and 14 in. long, had been made by casting vertically in a 12-cavity mold. For this loading, however, an improved horizontal casting method, with a 15-cavity mold, was developed (See Figure 3). This new casting method was developed because of the high reject rate caused by excessive porosity, cold shuts,

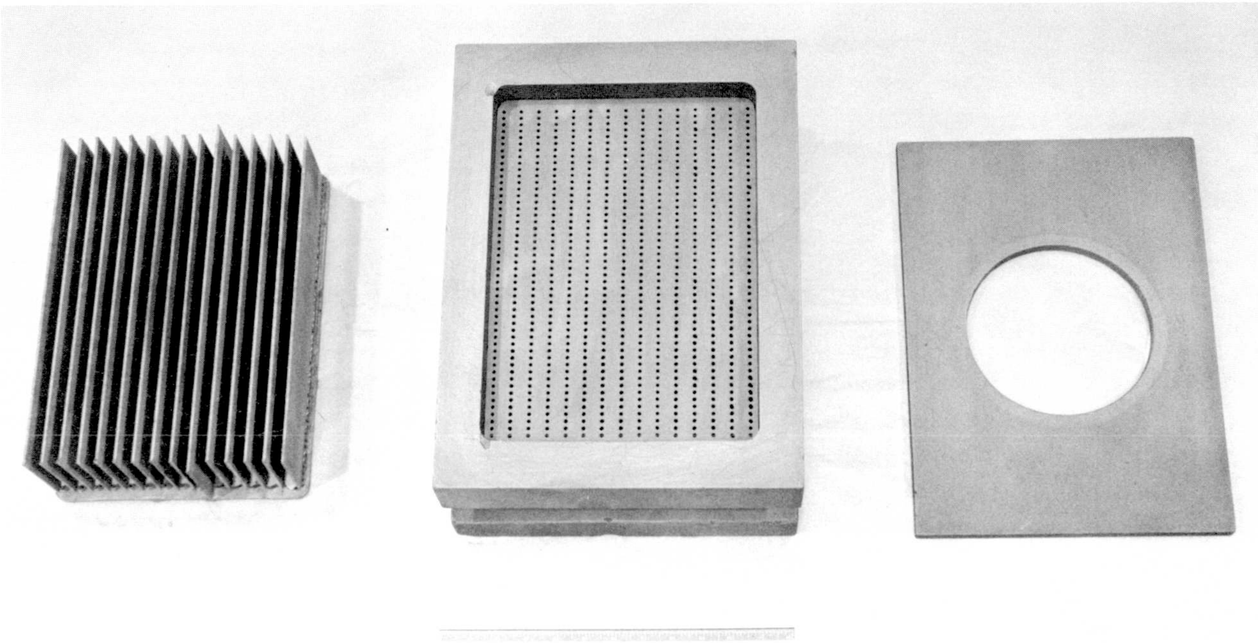

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Figure 3. Assembled Mold and As-Cast Fuel Plates Attached to Header

and differential grain size from top to bottom of the vertically cast plates. Vertical casting also restricted the number of plates that could be cast per heat; and mold life was unpredictable, due to the limitations of the vertical mold design. It was found that horizontal casting of the plates gave better control by eliminating the following conditions: (a) metal chilling, during the long drop of metal into the mold, and (b) poor mold temperature control.

The casting process described in Reference 1 essentially consists of vacuum induction melting uranium derby, molybdenum pellets, and other alloying additions, and casting into magnesium-zirconate-coated graphite molds preheated to 1850°F. Proper outgassing of all mold components was required, to insure good surface condition and sound metal with a minimum of internal porosity. This new concept of casting fuel plates horizontally on edge, using a specially designed, dual zoned, high frequency induction furnace, made casting of flat fuel plates of various dimensions practical on a production basis. A total of 696 fuel plates were cast, with an acceptable yield of 86%. After casting, fuel plates were radiographed to insure that there was no excessive internal porosity. Fuel plates were then machined on four edges. Samples were taken during final machining, and analyzed to insure that proper alloying had been achieved. Samples were also taken for density measurements and photomicrographs of grain size in the tops and bottoms of the plates.

TABLE I

NICKEL PLATING PROCEDURE

	Operation	Bath Composition	Temperature	Time	Remarks
1	Distilled water rinse	---	Ambient	30 sec	Vigorous agitation followed with pressure spray
2	Nickel Plate	$NiSo_4 \cdot 7H_2O$ - 40 oz/gal. $NiCl_2 \cdot 6H_2O$ - 4 oz/gal. H_3BO_3 - 4.5 oz/gal. H_2O_2 - as required pH = 3.8 to 4.2 Distilled water makeup	40-55°C	25 min Change contacts Plate additional 25 min	Current Density - 40 amp/ft^2 Tank anodes - bagged Dynel or nylon bags Cathode to enter bath with current on Agitation - clean air or argon, 0.2 ft/min-ℓ
3	Tap Water Rinse	---	Ambient	30 sec	Vigorous agitation
4	Distilled Water Immersion Rinse	---	Ambient	30 sec	Vigorous agitation
5	Distilled Water Immersion and Spray Rinse	---	Ambient	30 sec	Vigorous agitation followed with pressure spray
6	Alcohol Rinse	Absolute Ethanol or Methanol	Ambient	30 sec	Spray to cover all surfaces
7	Air Dry	---	Ambient	Until dry	Clean, filtered air under pressure may be employed
8	Nickel Strip	Enstrip A - 0.125 lb/gal. (proprietary cyanide compound of Enthone, Inc.) Tap water makeup	Ambient	Overnite, until stripped	Do not allow acids to come in contact with this solution or deadly HCN gas will be generated. Rinse wastes cannot be dumped without treatment.
9	Tap Water Rinse	---	Ambient	30 sec	Allow to drain dry

IV. NICKEL PLATING AND CLADDING PREPARATION

A. NICKEL PLATING

After final machining, the fuel plate cores were handled in the following manner:

1) The plates were cleaned by blasting with 50-mesh chilled steel grit.

2) After grit blasting, plates were ultrasonically cleaned in trichlorethylene to remove any grit.

3) Nickel was then electrodeposited on the prepared surfaces, using a specially designed plating rack. The plating rack permitted changing contact points during plating without interrupting the current (Figure 4). Table I details the plating steps used to produce a satisfactory nickel plate.

4) Nickel deposits were scanned for thickness, using a Dermitron eddy current thickness gauge. Typical nickel thickness profiles ranged from 0.0015 in. in the center of the fuel plate, to 0.002 in. at the extreme outer edges.

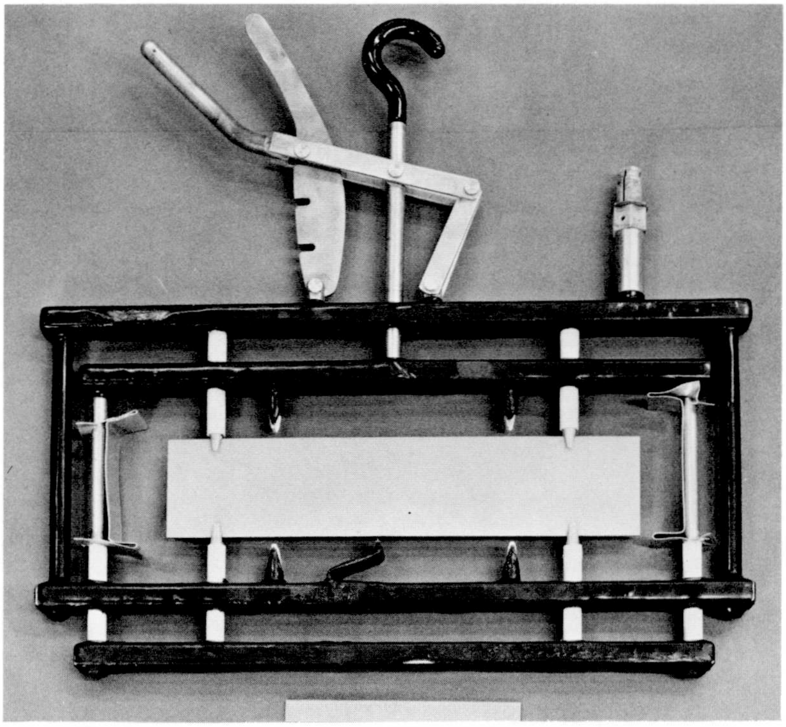

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Figure 4. Fuel Plate in Nickel Plating Rack

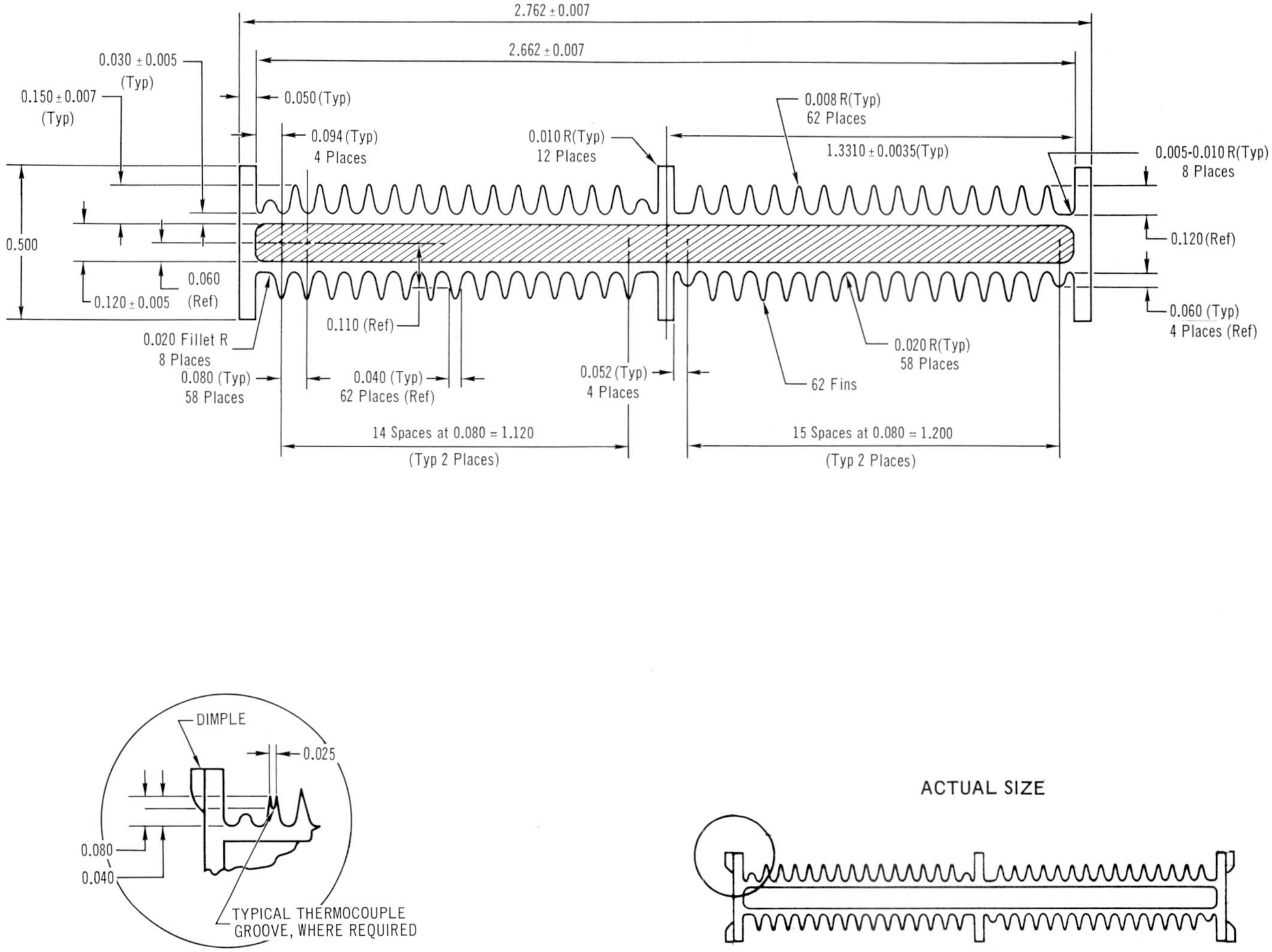

Figure 5. Aluminum Cladding Cross Section

B. CLADDING PREPARATION

The cladding, which is metallurgically bonded to the fuel core in this element, acts only as an envelope to retain fission products and to prevent contamination of the coolant. Although Type 1100 aluminum alloy has no inherent strength, it performs well in this fuel concept, where the fuel itself acts as the structural member. The aluminum cladding cross section shown in Figure 5 was formed by extrusion. Extruded 15-ft lengths were sawed into shorter lengths with a high speed metal saw, using sprayed kerosene as the lubricant. Prior to assembly, the cladding and end plugs were cleaned as described in Table II.

After the fuel core was nickel plated and all cladding components cleaned, the fuel core was carefully inserted into the cladding. During all phases of assembly, the core and cladding components were handled with lint-free cotton gloves to prevent the bonding surfaces from becoming contaminated. Figure 6 shows the assembly steps. After the end plugs and evacuation tube were put in place, the entire assembly was welded. It was necessary to weld a Type 5052 aluminum evacuation tube to one end plug, for vacuum outgassing prior to pressure bonding. The end plugs and evacuation tube were welded to the cladding, using specially designed copper welding chill blocks (See Figure 7). The water-cooled welding chill prevented the end plugs and the nickel plated fuel section from being overheated and oxidized during welding. After fuel sections were sealed in the cladding, they were outgassed to less than 50μ at 1000°F for several hours. The evacuation tube of Type 5052 aluminum was then hot knifed off, to seal the entire assembly. This produced an evacuated, sealed assembly, ready for hot-pressure bonding.

TABLE II

CLADDING COMPONENT SURFACE CLEANING PROCEDURE

	Operation	Applicable Aluminum Alloy	Bath Composition	Temperature	Time	Remarks
1	Vapor Degrease	All	Trichlorethylene vapors	180-190°F	10 min	Parts may be sprayed with clean trichlorethylene following vapor immersion
2	Alkaline Etch	All	12 oz/gal. Oakite "160" (proprietary material of Oakite Products)	60-70°C	1 min	
3	Tap Water Rinse	All	---	Ambient	30 sec	Use vigorous agitation
4	Nitric Acid Clean	All	6 to 8 normal HNO_3 (50 vol%)	Ambient	2 min	Periodically move parts in bath
5	Tap Water Rinse	All	---	Ambient	30 sec	Use vigorous agitation
6	Ammonium bifluoride desmut	Type 6061 alloy only. Omit Steps 7 and 8 for Type 1100 and Type 5052 alloys.	1.25 lb/gal. ammonium bifluoride	Ambient	2 min	Periodically agitate parts in bath
7	Tap Water Rinse	Type 6061 alloy only	---	Ambient	30 sec	Use vigorous agitation. Repeat Steps 5 and 6 and resume with Step 9
8	Distilled Water Rinse	All	---	Ambient	30 sec	Use vigorous agitation
9	Distilled Water Spray	All	---	Ambient	30 sec	Be sure that all surfaces are thoroughly rinsed
10	Alcohol Rinse	All	Absolute methanol or ethanol	Ambient		Spray to cover all surfaces
11	Air Dry	All	---	Ambient	Until dry	Clean filtered air under pressure may be used

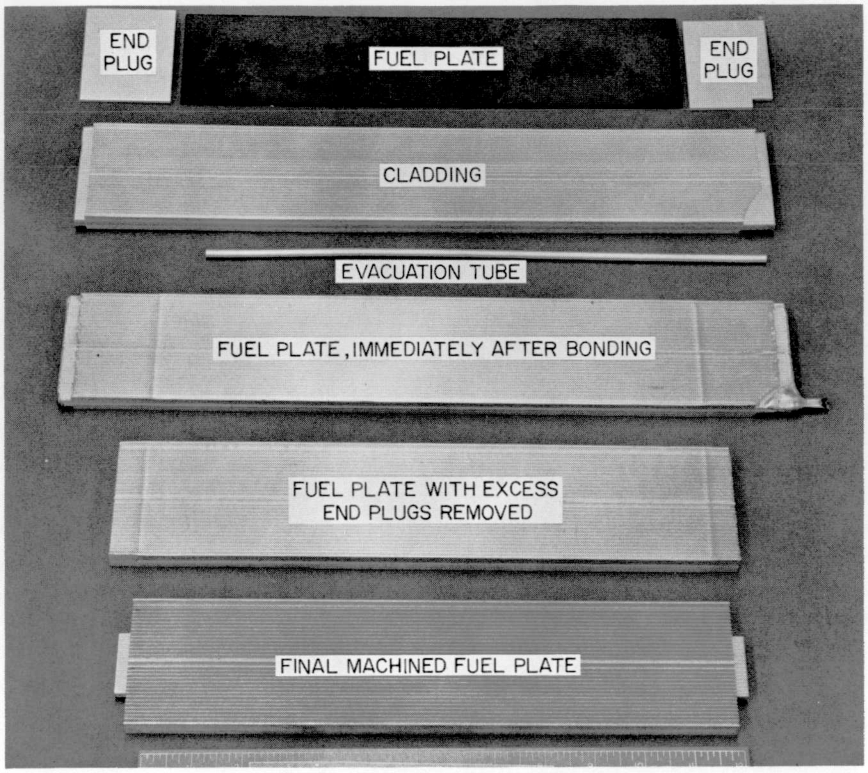

Figure 6. Typical Fuel Plate Assembly

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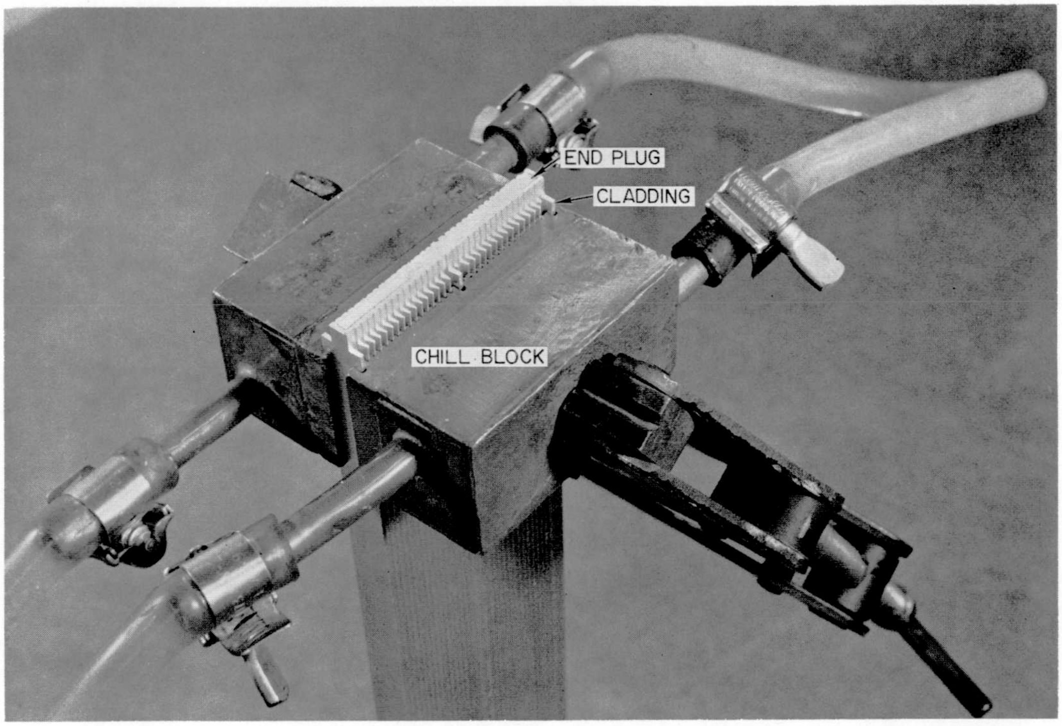

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Figure 7. Chill Blocks Used in Welding Fuel Sections

V. HOT PRESSURE BONDING

The isostatic pressing equipment consisted of a pressure vessel, 6 in. ID, 13.5 in. OD, and 18 in. effective inside depth, contained in a 33-kw air circulating furnace. The air circulating heating principle of the furnace made it possible to maintain a temperature of 1000 ± 10° F over the entire pressure vessel. Figure 8 shows the furnace setup and the pressure vessel head being lowered into the furnace.

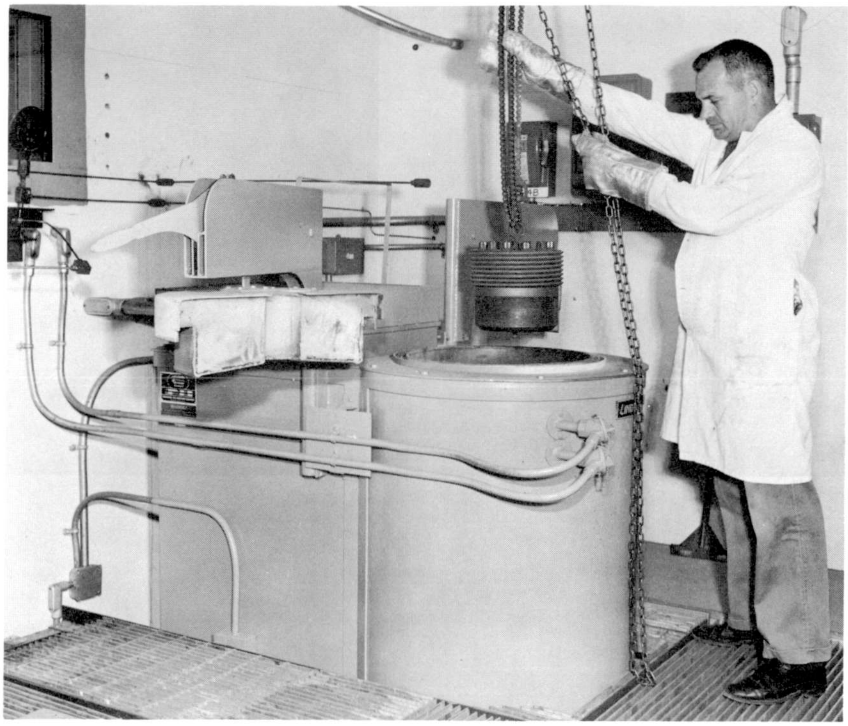

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Figure 8. Pressure Bonding Furnace

Prior to pressure bonding, the furnace and pressure vessel were heated to a uniform temperature of 1000°F. After the pressure vessel and furnace reached 1000°F, they were held at this temperature at least 12 hr, to assure even distribution of the heat throughout the vessel and vessel head assembly. After preheating the vessel and furnace, eight fuel sections were placed in the pressure vessel, and the vessel head was secured to the vessel. The fuel sections were allowed to preheat, at least 30 min, before pressure was applied. At the end of the 30-min preheat, the fuel sections were pressurized to 8000 psi with argon gas, and held at this pressure for 20 min. After the fuel sections were soaked at pressure and temperature for the prescribed length of time, the pressure was reduced to atmospheric, and the bonded fuel sections were immediately removed from the pressure vessel. Evidence of blisters in the cladding, upon visual examination of the hot-pressed fuel section, was cause for immediate rejection. Blistering clearly indicated an unbonded area.

VI. MACHINING AND FINAL ASSEMBLY

After bonding was completed, the excess end plug was cut from each end of the bonded fuel plate. These end sections were identified, and were given a peel test to determine whether the fuel plates were bonded. The peel test consisted of driving a sharp object into the interface between the cladding and the end plug. If no separation occurred, the fuel plates were considered bonded (Figure 9).

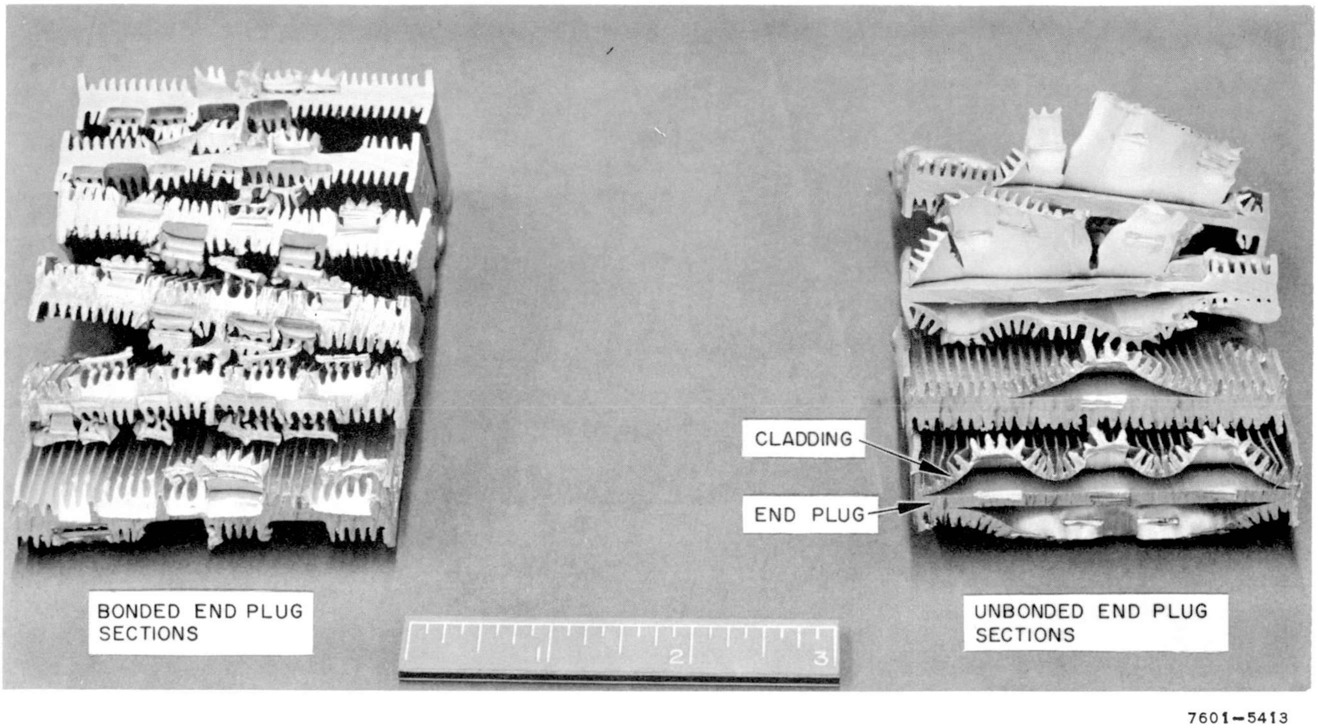
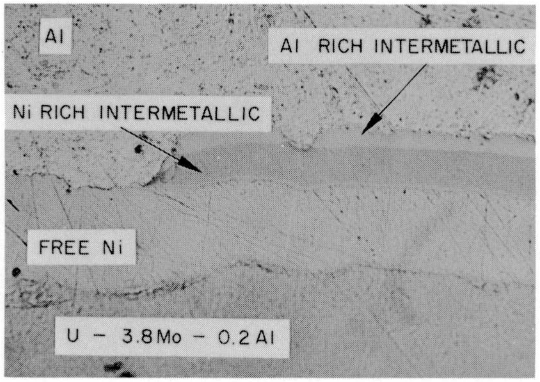


Figure 9. End Plugs After Peel Testing

The peel test was found to be the only satisfactory method of determining whether the fuel plates were bonded after the hot pressing operation. In the early stages of the bonding development, the peel test on the end plugs was checked against metallographic examination of the Al-Ni-U bond, and there was found to be an excellent correlation between the bond in the end plug and the bond in the fuel section. During the fabrication phase of this program, fuel plates were selected at random and sectioned, so the Al-Ni-U bond zone could be examined metallurgically. In all cases where the peel test indicated bonding, the bond between the Al-Ni-U was also found to be satisfactory. The photomicrographs in Figure 10 show typical Al-Ni-U diffusion bonds. Fuel plates were then machined to final



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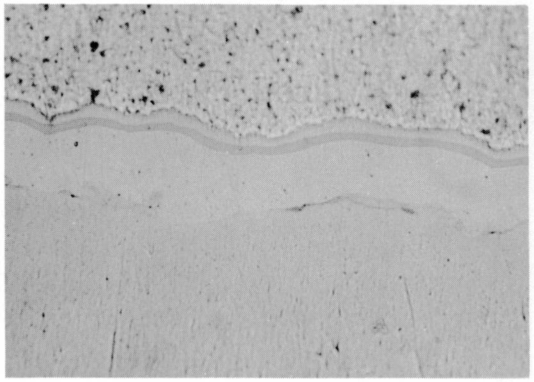
a. T = 1000°F, P = 7000 psi,
t = 25 min



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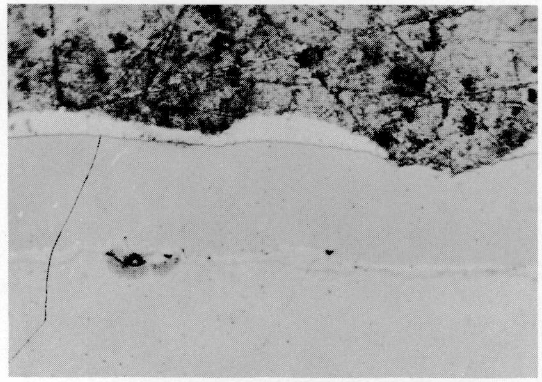
b. T = 1000°F, P = 8000 psi,
t = 25 min



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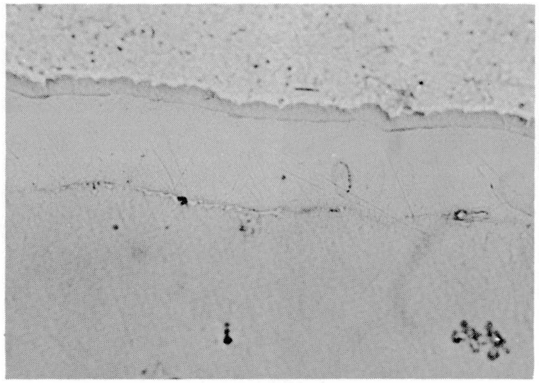
c. After Bonding 24 hr at 1000° F



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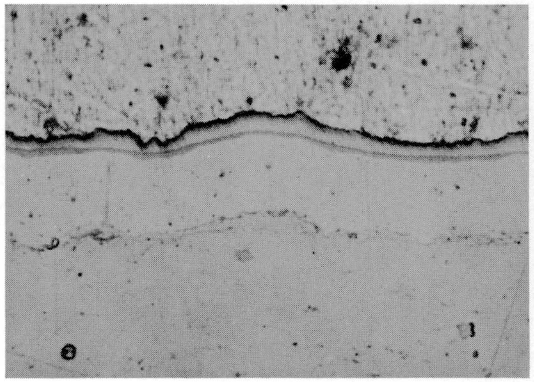
d. T = 1000°F, P = 7000 psi,
t = 35 min



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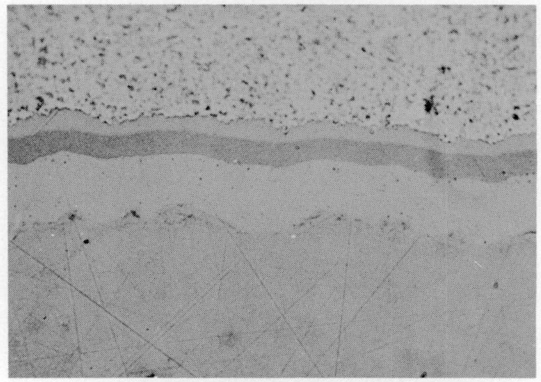
e. T = 1000°F, P = 8000 psi,
t = 35 min



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f. T = 1050°F, P = 8000 psi,
t = 35 min

Figure 10. Al-Ni-U Diffusion Zones (Photographed at 500X, Reduced to 340X)

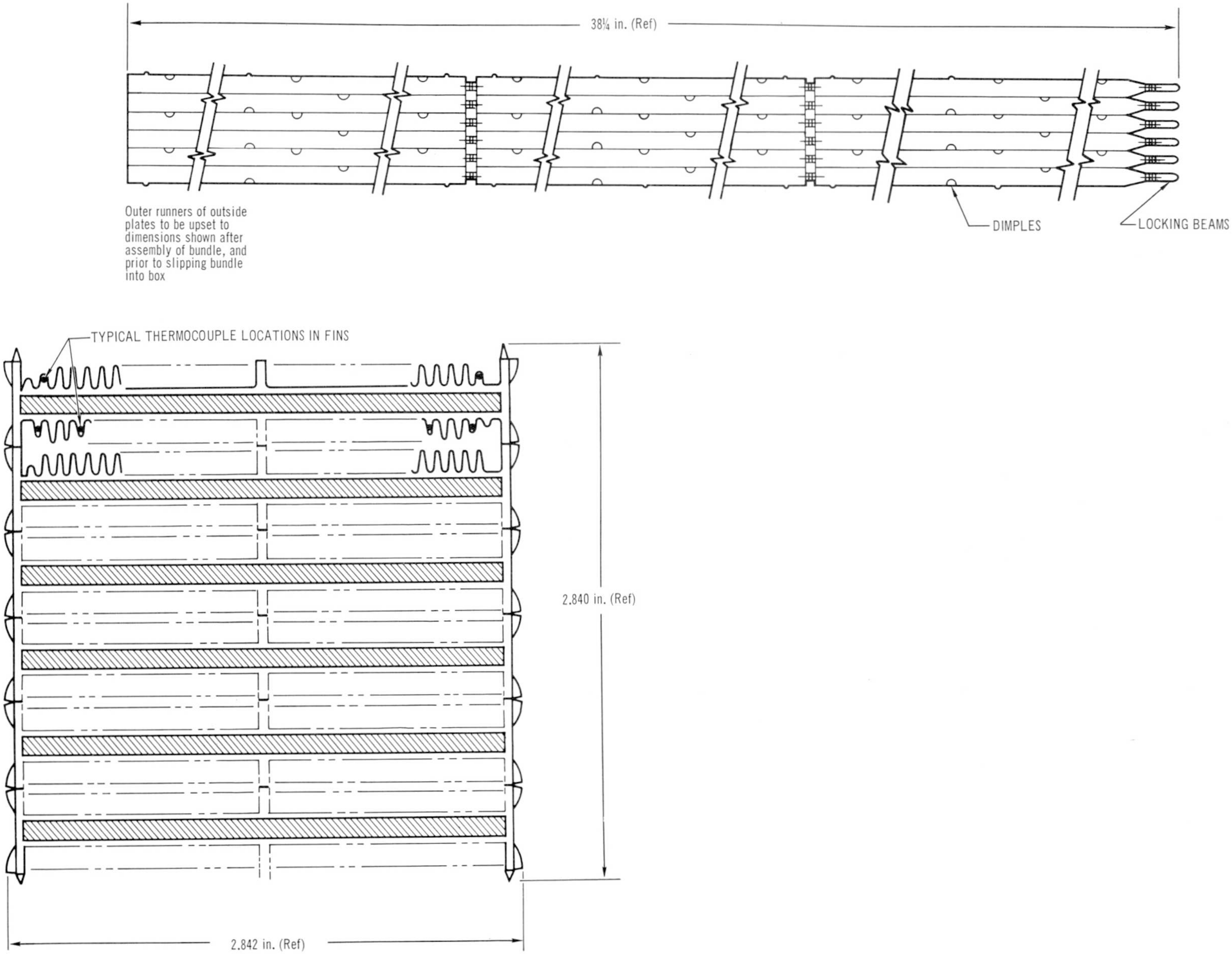

Figure 11. Fuel Bundle Layout

dimension. Longitudinal thermocouple grooves were cut, as required, into the fins (Figure 5). After final machining, the fuel plates were autoclaved in 10 to 20 lb steam pressure for a minimum of 2 hr. If any swelling of the fuel or cladding was exhibited, the plates were rejected.

Prior to final assembly, the fuel plate outer support cladding runners were dimpled and then dimensionally inspected. After the fuel plates were final inspected, the thermocouples were inserted in the split fins, and the fins were folded over the thermocouples.

The completed fuel plates were assembled into a fuel bundle, three plates long and six plates high (Figures 11 and 12). The three plate bundles were joined by a piano hinge type joint at the plate junction. The fuel plates were held in a stack by dimples in the outer runners. These dimples centered the fuel bundle in the fuel box, and prevented the plates from nesting. Small upsets on the outer runner of the top and bottom fuel plate in each section of the fuel bundle, in conjunction with the dimples, assured a snug fit between the fuel bundle and the fuel box.

The fuel box consisted of a single sheet of Type 347 stainless steel, formed and welded on one seam and drawn to final dimensions. At the lower end of the box were 12 pairs of holes. The holes provided places for plug welding the box to stainless steel locking beams which were attached to the last plate in each stack.

These plug welds secured the six fuel plates to the stainless steel fuel box, and still allowed the fuel plates to grow during reactor operation. After the fuel bundle was secured in the fuel box, the fuel element end hardware was attached to the fuel box. A special fixture was developed for this operation; as the maximum misalignment allowed, over the entire length of the fuel element, was only 0.060 in. Figure 13 shows the completed fuel element.

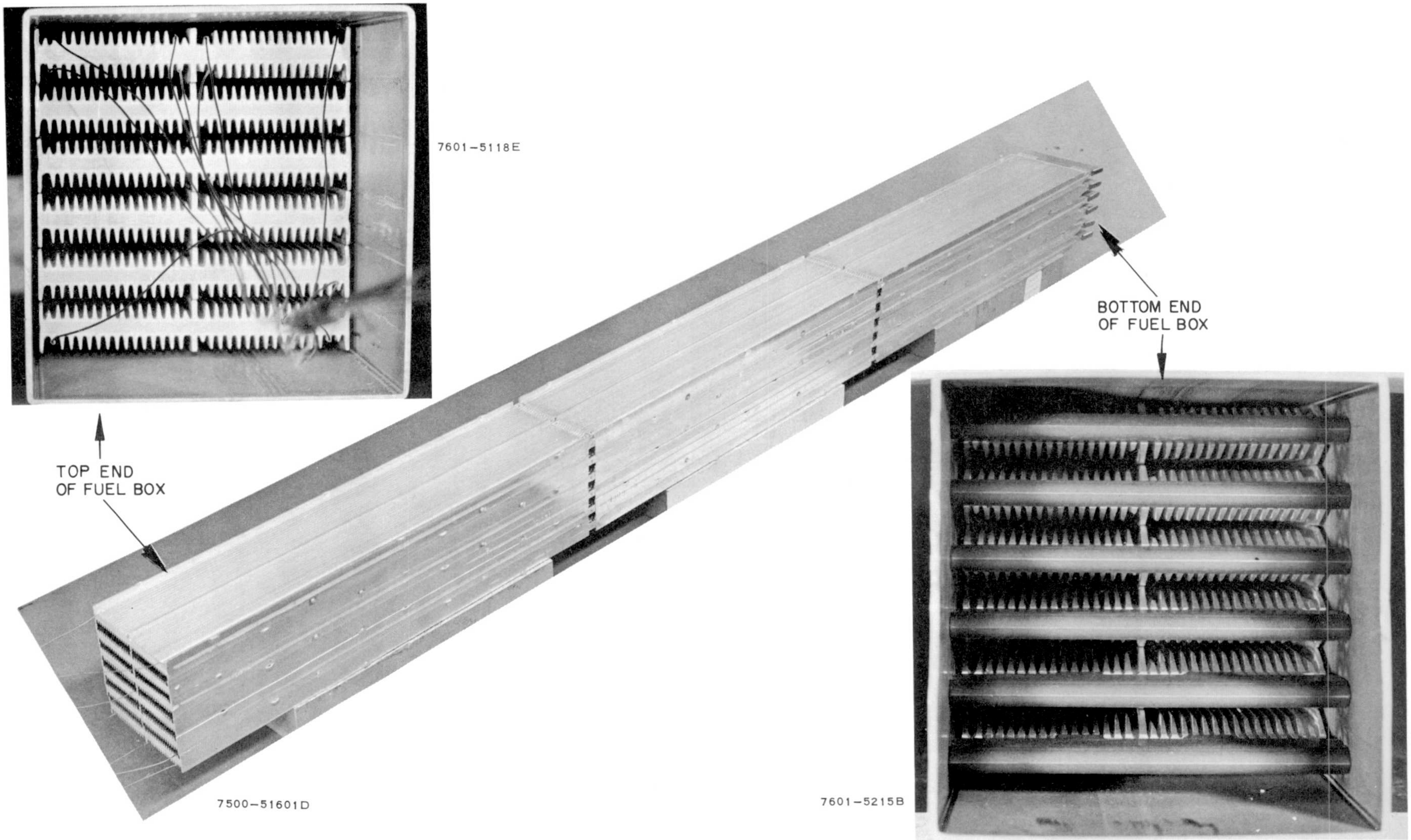

Figure 12. Thermocoupled Fuel Bundle

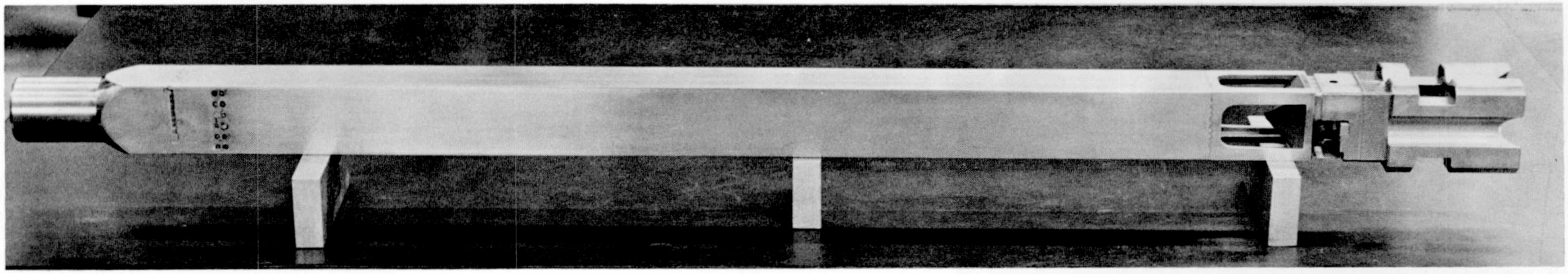

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Figure 13. Completed Fuel Element

VII. PACKAGING AND SHIPPING

The completed fuel elements were final inspected, cleaned, packaged, and shipped to the OMRE site. The exterior box surfaces of the elements were cleaned, using emery paper and acetone, and then handled with clean cotton gloves. The fuel elements were sealed in plastic bags containing argon gas. The elements were shipped, three elements per container.

VIII. INSPECTION AND QUALITY CONTROL PROCEDURES

Each phase in the fabrication of the elements was controlled by careful inspection, to insure the desired quality and conformance to product specifications.

A. THERMOCOUPLES

To insure the utmost reliability in the thermocouples, prepared for and installed in the OMRE, a procedure was developed for these thermocouples. Each thermocouple received was immediately assigned an identification number. The supplier's name and the purchase order number were recorded. All thermocouples purchased were in accordance with AI specification. The insulation resistances of the thermocouples were then measured, wire to wire and wire to sheath, at 500 v, and the resistances were recorded. At this time, a hot junction was made and visually inspected. The hot junction was quench tested through 25 cycles. The quench test consisted of heating to 900°F, air quenching to 400°F, and water quenching to room temperature. The reaction pattern of the thermocouple was recorded, enabling immediate detection of any malfunction of the thermocouple. Should a malfunction occur, the thermocouples were set aside for rework. The thermocouple loop resistance was then rechecked, and it had to equal the loop resistance prior to quench testing. Thermocouples were selected at random and x-rayed. Thermocouples, having successfully passed all tests to this point, were one-point calibrated at 850°F in the standards laboratory. If any thermocouple varied more than ±5°F from the standard, it was returned for rework. The calibrated thermocouples were then installed in the fuel elements. After the thermocouples were completely installed, their resistances were measured and compared with resistances taken before they were installed.

B. RAW MATERIALS

The weight, number of derbies, and segments of derbies were checked and recorded as received. Five-gram samples were drilled from each derby and retained until the casting program was completed. Composite samples, of 0.5g from three derbies, were analyzed for isotopic (U^{235}) content. The supplier's isotopic and impurity analyses were reviewed for conformance to specification.

The molybdenum and aluminum alloying elements were sampled, and the supplier's analyses were reviewed for conformance to specification.

All raw stock items were dimensionally inspected for conformance to purchase order requirements, and were visually inspected for identity and conformance. All raw materials required certified test reports, showing conformance of procurement specification requirements.

C. CAST FUEL PLATES

All cast fuel plates were properly identified, and identification records were maintained, so that every plate could be traced to the melt from which it originated. Each fuel plate was radiographed, and the radiographs kept in a permanent file. Samples were taken from the top and bottom of a special test plate which was cast in each heat. The samples were analyzed for carbon and other alloying elements. Samples were also taken from one plate in each heat for microscopic examination, to determine grain size, inclusion, segregation, and microstructure. Samples were to be identified and held until the core has been reclaimed.

The hardness and density of one sample from each heat were taken and recorded. Each plate was dimensionally and visually inspected, to assure conformance to drawing requirements. The plates were weighed, and the weight was recorded to the nearest 0.1 g.

D. ALUMINUM FUEL CLADDING

The supplier's certifications were reviewed, to assure conformance to specification requirements. Each shipment received was visually and dimensionally inspected, to assure conformance to drawing and specification requirements.

E. NICKEL PLATING CAST FUEL PLATE

The nickel plating was visually examined for uniformity and continuity. The plating thickness was measured with the "Dermitron" (manufactured by Unit Process Assemblies, Inc.).

F. FUEL PLATE ASSEMBLY

The nickel plated fuel plates and aluminum components were examined for cleanliness. Fuel plate identification numbers were checked. All welds were helium leak tested to AI Specification No. NA0115-006.

G. TESTING BONDED FUEL PLATE

Processing data were examined, to assure that the established bonding process was followed. The bonded fuel plates were visually examined for blisters. The machined plates were visually and dimensionally inspected for conformance to the drawing. Samples were cut from the end plugs of each plate, and were peal tested to determine the quality of the aluminum-to-aluminum bond. Each finished plate was subjected to the autoclave test, and then was visually examined for evidence of cladding failure.

H. FUEL ELEMENT ASSEMBLY

All components and subassemblies were visually inspected, at the time of assembly, for cleanliness and surface finish. Fuel plate locations were recorded. The completed assembly was dimensionally inspected, and all closure welds were dye-penetrant inspected. All moving parts were operated to assure proper installation. Thermocouples were checked for proper installation.

I. PACKAGING AND SHIPPING

Shipping containers were checked, to assure that they met AEC and ICC regulations, and that the elements would not be damaged during transit.

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