ESADA FUEL FABRICATION DEVELOPMENT PROGRAM

TERMINAL REPORT

Volume IV

UC Fuel Rod, Element, and Assembly –
Development and Production

By

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ABSTRACT

An economically attractive process was developed and demonstrated for the production of stainless steel-clad, sodium-bonded, uranium carbide fuel elements, for use in large sodium graphite reactors. Over 400 fuel rods for full-scale 18-rod elements were produced, and elements were assembled at a rate of approximately five per week, to demonstrate the process and associated costs.

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I. INTRODUCTION

The production of uranium carbide fuel elements involves three major work areas: (a) melt stock production, (b) slug production, and (c) the fabrication of fuel rods, and their assembly into elements. This report covers the last area.

The objectives of this project were to develop and demonstrate a process for fabricating fuel rods and assembling fuel elements which was consistent with a cost goal of \$100/kg of contained U in the finished element. Fabrication processes were to be conducted, using the same nuclear safety criteria as would be applied to ~ 5% enriched fuel. The demonstration phase was based upon a projected production rate equivalent to 200 fuel elements per year, using depleted uranium carbide.

The process for fabricating rods consisted of:

- a) Loading cast and machined UC fuel slugs into thin-walled stainless steel cladding tubing which were closed by welding at their bottom ends
- b) Filling the 0.025 in. annulus between the fuel and the cladding with molten sodium, the thermal bond medium
- c) Closing the upper end by welding
- d) Nondestructive inspection, which included an eddy current technique for determining the sodium bond quality.

The basic techniques for sodium filling, cladding, fuel rod handling, end closure welding, and nondestructive testing of the fuel rod bond had been developed for HNPF Core I. Experience was also gained from the fabrication of the 10 enriched UC elements for Hallam Core I.

Cost reduction, without compromising quality, was a primary goal of the ESADA program; and, since sodium-bonded fuel elements had already been produced, new methods were introduced only in those areas where the existing methods required improvement or were inherently costly. An example of such an area was the method of recovering fuel slugs from rejected fuel rods, for which completely new technique was developed during this program. Limited development work was also performed on the sodium filling process.

TABLE I
TYPICAL PROCESS STEPS FOR UC SODIUM BONDING

Sequence	Operation	Temperature (°F)	Time (hr)	Atmosphere	Description
1	Bottom end closure weld	Ambient	Not critical	Standard Heliarc welding head	Cladding tubing purchased to finished length with square, deburred ends. End caps finish machined, at assembly, to a light press fit in cladding end. Gear-driven welding fixture, with copper chill fitted to cladding exterior, used to rotate fuel rod in air while welding accomplished with Heliarc head at 20 to 40 amp current.
2	Fuel batching	Ambient	Not critical	Air	Fuel slugs manually placed end-to-end to form full column length, as per blueprint for one fuel rod. Weight and heat numbers recorded.
3	Fuel loading	Ambient	Not critical	Air	Fuel slugs manually inserted into open cladding end, while cladding tube supported over its full length at an angle of 15° to the horizontal, open end up.
4	Retort loading	Ambient	Not critical	Air	Fuel rods placed inside vacuum bonding furnace (60-rod retort, for production), using circular steel rack (retort lazy susan) as handling device.
5	Heating and evacuation	Up to 500-700	4 to 8	Vacuum	Heating and evacuation proceed simultaneously. Maximum temperature held for 2 to 4 hr.
6	Na pouring	500 to 700	Max. - 8 Normal-2 to 4	1 μ	Liquid Na, at temperature of 275 to 325°F, poured into each rod in turn, using pour tube and valve. Sodium filtered through 5- μ mean pore opening sintered stainless steel filter, immediately prior to entering fuel rod, to reduce oxygen content. Each rod filled until sodium visible through vessel windows.
7	Na suction	300 to 450	Max. - 8 Normal - 2	Helium	Suction tube lowered into each fuel rod, to a mechanically preset level, and sodium removed to level finally required in gas space.
8	Top end closure welding	Ambient	Max. - 8 Normal - 3	80% He - 20% A by pressure, 1 atm total	End caps manually inserted, using gloves in vessel. Welding done in vessel, with specially designed welding head and drive mechanism.
9	Leak testing, visual and dimensional inspection	Ambient		Air	Helium leak test of upper cap weld; visual inspection for cladding handling damage, conventional dimensional inspection.
10	Na bond inspection	350		Air	As described under "Eddy current nondestructive bond testing".

II. EXPERIMENTAL FABRICATION

A. SODIUM BONDING IN THE 10- AND 60-ROD RETORTS

Table I gives a brief description of the fuel rod fabrication process steps, with typical values and ranges for the main variables. The major pieces of equipment used were a 10-rod development bonding retort and a 60-rod production bonding retort. The latter is pictured in Figure 1. The chief variables are time, temperature, sequence of the fuel rod sodium-filling operations, and the fuel preparation. Tables II and III list the bonding experiments, with their variables and results.

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Figure 1. 60-Rod Bonding Retort

The early experiments used slugs which were machined with an oil coolant, and which were stored under oil. Since complete removal of the oil was required, degreasing and vacuum outgassing of the fuel was required, and this created a bonding problem. Later work, on dry machining and storage methods, eliminated oil from all process steps, and hence the need for both degreasing and outgassing.

B. SODIUM BONDING IN QUARTZ TUBES

Several rods were experimentally sodium bonded, using quartz tubing as the cladding material, rather than stainless steel, to permit visual examination of the sodium filling and the bonding process.

A low-temperature, single-rod furnace, illustrated in Figure 2, was designed and built for this work. The equipment used for adding sodium was identical to that used for bonding in the multiple-rod retorts. A typical operational sequence for filling a quartz fuel rod is given in Table IV. Table V lists the experiments, with their variables and results. The temperature at which these experiments could be conducted was limited to about 500°F, because of discoloration of the quartz tubing.

TABLE II

EXPERIMENTS IN THE 10-ROD RETORT TO DETERMINE SODIUM BONDING CHARACTERISTICS OF UC FUEL TO TYPE 304 STAINLESS STEEL CLADDING

Fuel Rod Sequence Number	Type 304 Stainless Steel Cladding		Fuel			Fuel Preparation Prior to Bonding	Vacuum, Heat, and Sodium Fill Statistics	Radar Eddy Current Trace and Visual Bond Results	
	Length (ft)	Diameter (in)	Length (in.)	Diameter (in)	Weight (g)				
Run No. 7 — Started 9/13/62, Completed 9/14/62									
Rod No. 9						New UC fuel slugs	Retort vacuum of 0.1 μ maintained for 1 hr at 650°F, prior to sodium pouring. Retort back-filled with 1 atm of helium, then heated to 750°F for 2 hr, after sodium pouring.	Trace indicated cluster of small and closely packed voids, extending along lengths of Slugs No. 7, 17, and 27 (numbered from top of fuel column). No indication of void as large as 1/8 in. in diameter	
Rod No. 10									Same trace indication as Rod No. 9, however, only two slugs contained cluster of small voids.
Rod No. 11	16	Wall-0.010 ID-0.540	159	0.500		Fuel reclaimed from a previous bonding trial. Fuel cleaned with butyl alcohol and methanol.	Bubbling action occurred during sodium pouring of Rods No. 11 and 12.	Trace indicated 50% of rod contained clusters of small voids, similar to those in Rods No. 9 and 10. Half of these voids were greater than 1/8 in. in diameter, but less than 3/16 in. in diameter	
Rod No. 12									Trace indicated 50% of rod contained clusters of small voids, similar to those in Rods No. 9 and 10. Some of these voids were nearly 1/4 in. in diameter. Hot radac traces, before and after vibration testing, indicated little effect on dispersing or removing voids. Rod x-rayed at room temperature and 350°F, to determine sodium level. Sodium level 2 in. cold (70°F), and 2-5/8 in. at 350°F.
Run No. 8 — Started 9/22/62, Completed 9/24/63									
Rod No. 13						Fuel for Rods No. 13, 14, 15, and 16 was new. Loaded fuel rods were placed in retort and heated to 650°F under 0.1 μ . Outgassing continued over weekend.	Retort vacuum of 0.1 μ maintained for 1 hr at 650°F, prior to sodium pouring. Retort back-filled with 1 atm of helium, then heated to 750°F for 2 hr, after sodium filling.	Trace indicated 8 to 10 small voids, well dispersed along a 5 ft length near center of rod, before and after vibration testing. X-ray revealed sodium level to be 1-3/4 in. at 70°F, and 2-1/16 in. at 350°F.	
Rod No. 14								Traces, both before and after vibration testing, revealed fewer inhomogeneities in the sodium bond than in Rod No. 13. Those indicated were considerably less than 1/8 in. in diameter. X-ray revealed sodium level to be 2-11/16 in. at 70°F, and 2-3/4 in. at 350°F	
Rod No. 15	16	Wall-0.010 ID-0.540	159	0.500				First trace, before vibration testing, indicated two voids of borderline size, when compared to trace of 1/8 in. diameter void in standard rod. Trace, after vibration testing, indicated voids had been dispersed into smaller voids, along a 6-in. section. Radiograph showed sodium level to be 2-1/8 in. at 70°F, and 2-1/8 in. at 750°F	
Rod No. 16								Traces revealed this rod to be within tentative specifications. Before vibration testing, two areas of closely packed voids, up to 3/16 in. in diameter, appeared. These dispersed to less than 1/8 in. in diameter after vibration. Radiograph revealed sodium level to be over 9 in. at 70°F, and over 9 in. at 750°F. Sodium level projecting over edge of film preventing accurate measurement.	
Run No. 9 — 10/17/62									
Rod No. 27					6,745.00	Trichlorethylene degreased for 5 hr, no outgassing	650°F retort temperature indicated at all heater zones before sodium pouring. Vacuum held at 0.1 μ . Temperature increased to 750°F after sodium pouring, and allowed to soak for 2 hr. Retort allowed to cool to 150°F before removing rods.	All six rods of Run No. 9 were hot eddy current bond tested. The traces of Rods No. 27, 29, 30, 31, and 32 appeared to contain no inhomogeneities as large as the traces of the 1/8, 3/16, and 1/4 in. in diameter Nichrome wires in the standard rod. Rod No. 28 indicated a single borderline sodium defect in the annulus at Slug No. 12. Stripping showed a 1/4 by 3/16 in. lack of sodium bond area on the slug. This rod was not hot vibrated to remove defect, in order to correlate visual defects with Radac trace indications	
Rod No. 28					6,728.95				
Rod No. 29					6,731.62	Degreased, followed by 2-hr outgas at 1000°F	500°F retort temperature indicated at all heater zones before sodium pouring. Vacuum held at 0.1 μ . After sodium pouring, retort helium backfilled and allowed to cool to 150°F before rod removal.		
Rod No. 30					6,757.21				
Rod No. 31	16	Wall-0.010 ID-0.540	159	0.500		Hexane degreased for 3 hr.	500°F retort temperature indicated at all heater zones before sodium pouring. Vacuum held at 0.1 μ . After sodium pouring, retort helium backfilled and allowed to cool to 150°F before rod removal.		
Rod No. 32						Hexane degreased for 3 hr			
Run No. 10 — 11/2/62									
Rod No. 01			41 slugs		6,747.87	Trichlorethylene degreased for 0.5 hr, followed by 2-hr outgassing at 1000°F.	500°F retort temperature indicated at all heater zones before sodium pouring. Vacuum held at 0.1 μ . Bubbles appeared at surface during pouring operation. Retort cooled to 150°F before rod removal	Rods No. 01 through 08 were considered acceptable to tentative specifications. Rod No. 04 showed gross inhomogeneities, larger than 1/8 in. in diameter, for almost the entire rod length. Visual examination after stripping proved these inhomogeneities to be lack of bonding. Rod No. 02 was one of the cleanest, by eddy current bond test and by visual inspection after stripping. Radac traces of Rods No. 01 through 08 were compared against a standard rod profile which contained 1/8 and 1/4 in. in diameter quartz pins, swaged into the fuel slugs and extending 0.005 to 0.042 in. from the slug surface into the annulus.	
Rod No. 02			63 slugs (159 in.)		6,747.40				
Rod No. 03	16	Wall-0.010 ID-0.540	43 slugs	0.500	6,766.36				
Rod No. 04			57 slugs		6,766.36				
Run No. 11 — 11/28/62									
Rod No. 05					6,768.28	Trichlorethylene degreased for 0.5 hr, followed by 1-hr outgassing at 1000°F.	500°F retort temperature indicated at all heater zones before sodium pouring. Vacuum held at 0.1 μ . After sodium pouring, retort helium backfilled and allowed to cool to 150°F before rod removal.	Rods No. 01 through 08 were considered acceptable to tentative specifications. Rod No. 04 showed gross inhomogeneities, larger than 1/8 in. in diameter, for almost the entire rod length. Visual examination after stripping proved these inhomogeneities to be lack of bonding. Rod No. 02 was one of the cleanest, by eddy current bond test and by visual inspection after stripping. Radac traces of Rods No. 01 through 08 were compared against a standard rod profile which contained 1/8 and 1/4 in. in diameter quartz pins, swaged into the fuel slugs and extending 0.005 to 0.042 in. from the slug surface into the annulus.	
Rod No. 06					6,823.28				
Rod No. 07	16	Wall-0.010 ID-0.540	159	0.500	7,098.68				
Rod No. 08					6,770.81				

TABLE III

EXPERIMENTS IN THE 60-ROD RETORT TO DETERMINE SODIUM BONDING CHARACTERISTICS OF UC FUEL TO TYPE 304 STAINLESS STEEL CLADDING

Fuel Rod Sequence Number	Type 304 Stainless Steel Cladding		Fuel		Fuel Preparation Prior to Bonding	Vacuum, Heat, and Sodium Fill Statistics	Radac Eddy Current Trace and Visual Bond Results										
	Length (ft)	Diameter (in.)	Length (in.)	Diameter (in.)													
Run No 7 — 1/3/63																	
Rods No. 48, 49, 50, 41 and 52	16	Wall-0.010 ID-0.540	159	0.500	Fuel and cladding out-gassed at 75° for 12 hr.	Retort vacuum of 0.5μ for 4 hr, prior to sodium pouring. Temperature of 500°F maintained for 2 hr before backfilling with helium. Sodium level 18 in. from top end of cladding	Trace indications for Rods No. 49, 50, 51, and 52 showed no inhomogeneities larger than 1/8 in. in diameter in the sodium annulus. Rod No. 48 trace showed large areas of inhomogeneities throughout the entire rod length, therefore, considered rejectable Cold traces showing slug lengths, slug surface, and end conditions, prior to sodium bonding, correlate with hot trace results after sodium pouring.										
Run E-X-1 — 2/22/63																	
Rods No. 31, 41 and 50	16	Wall-0.010 ID-0.540	159	0.500	Fuel and cladding out-gassed at 75° for 12 hr.	Retort vacuum of 0.5μ for 4 hr, prior to sodium pouring. Temperature of 500°F maintained for 2 hr before backfilling with helium. Sodium level 18 in. from top end of cladding.	Comparison of traces of Rods No. 31 and 41 with that of ESADA standard rod indicated all rods to be acceptable. However, the rods required hot vibration, to remove borderline inhomogeneities. X-ray sodium level results were: <table><tr><th>Rod No.</th><th>Hot Sodium Level (Inches above end of top fuel slug)</th></tr><tr><td>31</td><td>2-1/2</td></tr><tr><td>41</td><td>3</td></tr></table> Rod No. 50 could not be eddy current tested, because of damaged cladding.	Rod No.	Hot Sodium Level (Inches above end of top fuel slug)	31	2-1/2	41	3				
Rod No.	Hot Sodium Level (Inches above end of top fuel slug)																
31	2-1/2																
41	3																
Run E-X-2 — 3/4/63																	
Rods No. 37, 46, 53, and 60	16	Wall-0.010 ID-0.540	159	0.500	Slugs were first wet machined then degreased. Second operation, end facing and chamfering, was accomplished dry.	Retort vacuum of 0.5μ for 4 hr, prior to sodium pouring. Temperature of 500°F maintained for 2 hr before backfilling with helium. Sodium level 18 in. from top end of cladding	Rod No. 53 was rejected for a leak in the top end cap weld. Rods No. 37, 46, and 60 met all the hot eddy current specification requirements. X-ray sodium level results were: <table><tr><th>Rod No.</th><th>Hot Sodium Level (in.)</th></tr><tr><td>37</td><td>2</td></tr><tr><td>46</td><td>2-11/16</td></tr><tr><td>53</td><td>1-1/2</td></tr><tr><td>60</td><td>2-3/4</td></tr></table> Cladding surface condition acceptable, prior to fuel loading and after hot eddy current vibration and x-ray testing.	Rod No.	Hot Sodium Level (in.)	37	2	46	2-11/16	53	1-1/2	60	2-3/4
Rod No.	Hot Sodium Level (in.)																
37	2																
46	2-11/16																
53	1-1/2																
60	2-3/4																
Run E-X-3 — 3/5/63																	
Rods No. 32, 40, 49 and 58	16	Wall-0.010 ID-0.540	159	0.500	Fuel and cladding out-gassed at 75° for 12 hr.	Retort vacuum of 0.5μ for 4 hr, prior to sodium pouring. Temperature of 500°F retained for 2 hr, then reduced to 450°F. Retort zone heaters shut off, and retort allowed to cool overnight.	Trace indications for Rods No. 32, 40, and 58, when compared with the traces of the ESADA standard rod, showed all three to be acceptable. However, hot vibration testing had to be utilized, to remove questionable areas of inhomogeneities in the sodium annulus. Rod No. 49 was rejected for a leaky top end cap. X-ray sodium level results were: <table><tr><th>Rod No.</th><th>Hot Sodium Level (in.)</th></tr><tr><td>32</td><td>2-7/16</td></tr><tr><td>40</td><td>3-1/16</td></tr><tr><td>49</td><td>2</td></tr><tr><td>58</td><td>3-1/8</td></tr></table>	Rod No.	Hot Sodium Level (in.)	32	2-7/16	40	3-1/16	49	2	58	3-1/8
Rod No.	Hot Sodium Level (in.)																
32	2-7/16																
40	3-1/16																
49	2																
58	3-1/8																
Run E-X-4																	
	16	Wall-0.010 ID-0.540	159	0.500	Fuel and cladding out-gassed at 75° for 12 hr.	Retort vacuum of 0.5μ for 4 hr, prior to sodium pouring. Temperature of 500°F retained for 2 hr, then reduced to 450°F. Retort zone heaters shut off, and retort allowed to cool overnight.	No data available, due to a retort failure.										
Run E-X-5 — 4/17/63																	
Rods No. 36, 42, 50, and 58	16	Wall-0.010 ID-0.540	159	0.500	Fuel and cladding out-gassed at 75° for 12 hr.	Retort vacuum of 0.5μ for 4 hr, prior to sodium pouring. Temperature of 500°F retained for 2 hr, then reduced to 450°F. Retort zone heaters shut off, and retort allowed to cool overnight.	Rod No. 58 was rejected due to a leaky top end cap. X-ray sodium level results were: <table><tr><th>Rod No.</th><th>Hot Sodium Level (in.)</th></tr><tr><td>36</td><td>5-1/8</td></tr><tr><td>42</td><td>5-1/4</td></tr><tr><td>50</td><td>7-1/4</td></tr></table>	Rod No.	Hot Sodium Level (in.)	36	5-1/8	42	5-1/4	50	7-1/4		
Rod No.	Hot Sodium Level (in.)																
36	5-1/8																
42	5-1/4																
50	7-1/4																

TABLE III

**EXPERIMENTS IN THE 60-ROD RETORT TO DETERMINE SODIUM BONDING
CHARACTERISTICS OF UC FUEL TO TYPE 304 STAINLESS STEEL CLADDING
(CONTINUED)**

Fuel Rods Sequence Number	Type 304 Stainless Steel Cladding		Fuel		Fuel Preparation Prior to Bonding	Vacuum, Heat, and Sodium Fill Statistics	Radac Eddy Current Trace and Visual Bond Results
	Length (ft)	Diameter (in.)	Length (in.)	Diameter (in.)			
Run E-X-6 — 5/9/63							
Rods No. 1 through 60	16	Wall-0.010 ID-0.540	159	0.500	Fuel and cladding out- gassed at 75° for 12 hr.	Retort vacuum of 0.5μ for 4 hr, prior to sodium pouring. Tem- perature of 500°F re- tained for 2 hr, then reduced to 450°F. Re- tort zone heaters shut off, and retort allowed to cool overnight.	Trace results of the first series of 60 rods bonded simultaneously were: 45% Accepted 38% Rejected for voids in sodium annulus 10% Rejected for leaks in top end closure weld 03% Rejected for oversized top weldments 02% Rejected for low sodium level 02% Rejected for damaged cladding 100% Total
Run E-X-7 — 6/6/63							
Rods No. 1 through 60	16	Wall-0.010 ID-0.540	159	0.500	Fuel and cladding out- gassed at 75° for 12 hr.	Retort vacuum of 0.5μ for 4 hr, prior to sodium pouring. Tem- perature of 500°F re- tained for 2 hr, then reduced to 450°F. Re- tort zone heaters shut off, and retort allowed to cool overnight.	Trace results of the second series of 60 rods bonded simultaneously were: 77% Accepted 17% Rejected for damaged cladding 05% Rejected for leaks in top end closure weld 01% Rejected for oversized top weldments 100% Total
Run E-X-8 — 6/26/63							
Rods No. 60 through 112	16	Wall-0.010 ID-0.540	159	0.500	Fuel and cladding out- gassed at 75° for 12 hr.	Retort vacuum of 0.5μ for 4 hr, prior to sodium pouring. Tem- perature of 500°F re- tained for 2 hr, then reduced to 450°F. Re- tort zone heaters shut off, and retort allowed to cool overnight.	Trace results of the third series of 60 rods bonded simultaneously were: 77% Accepted 13% Rejected for leaks in top end closure weld 05% Rejected for mislocated fuel slugs 05% Rejected for damaged cladding 100% Total

7601-5401

a. Overall View

b. Closeup

7610-5405

Figure 2. Furnace for Visual Observation of Quartz Tubes

TABLE IV
TYPICAL OPERATIONS FOR SODIUM FILLING OF
QUARTZ-CLAD FUEL RODS

Sequence	Operation	Temperature of Fuel Rod (°F)	Time	Atmosphere Inside Rod (Air outside at all times)	Description of Operation
1	Fuel loading	Ambient		Air	Fuel slugs manually loaded into horizontal quartz tubing which was closed on bottom end
2	Furnace loading	Ambient		Air	Fuel rod manually loaded into vertical single-rod furnace, and open upper end of quartz fastened into O-ring vacuum seal at lower end of sodium handling apparatus
3	Evacuation and heating	Ambient to 300-500	2 hr	1 atm air to 10 ⁻² torr vacuum	Rod evacuated through sodium apparatus and heated simultaneously
4	Sodium filling	300-500	5 min	10 ⁻² torr vacuum	Sodium poured into upper end of rod, and visually observed as it flowed downward in annulus between fuel and quartz cladding. Pouring continued until Na present 3 to 6 in. above uppermost fuel slug. Annulus usually not completely filled at this point.
5	Pressurization	300-500	1 min	10 ⁻² torr vacuum to 1 atm He	Helium admitted into quartz tube above sodium. Sodium level usually dropped, and unfilled areas in annulus disappeared or became smaller.
6	Observation at filling temperature	300-500	10 min to 2 hr, depending on purpose of equipment	Vacuum or inert gas, depending on experimental purpose	Changes in sodium observed while temperature held constant, simulating soaking period in normal bonding cycle. Repeated evacuation and pressurization employed in some cases.
7	Cooling	300-500 to ambient	2 hr	1 atm He	Reduction in volume and formation of shrinkage voids observed in the sodium as it froze
8	Furnace unloading	Ambient		He	Vacuum seal broken, and quartz rod manually removed from vertical furnace. Since cladding was quartz, and rods were experimental only, no end closure welding performed. In most cases, completed rod was photographed, and broken to obtain chemical samples.

TABLE V

EXPERIMENTS IN SODIUM BONDING OF QUARTZ-CLAD UC AND STAINLESS STEEL SLUGS
IN SINGLE-ROD FURNACE

Fuel Rod Sequence Number	Quartz Tube		Fuel		Fuel Preparation Prior to Bonding	Heat And Vacuum Statistics	Na Pouring And Solidification Observation
	Length (ft)	Diameter (in.)	Length (in.)	Diameter (in.)			
1 10/15/62	16'	Wall-0.050 OD-0.550	159	0.500	Hexane Cleaned	Evacuate to 10 μ . 300°F bottom and 650°F top temperature. Oil condensate visible at cool end of quartz tube. Vacuum held at 60 μ .	<ol style="list-style-type: none"> 1. First drops of sodium caused discoloration after setting. 2. First sodium pouring settled, and required second pouring to top off level. 3. Many voids, of various diameters, appeared 1/3 down from top of sodium level. 4. Brown discoloration noted along quartz-to-sodium interface
2 6/27/63	4'	Wall-0.050 OD-0.550	Loading consisted of 30 in. of stainless steel slugs	0.500	Trichlorethylene degreased	Evacuate to 25 μ . Average sodium temperature 350°F.	<ol style="list-style-type: none"> 1. With vacuum in quartz tube, sodium refused to flow, with release of vacuum, sodium began to flow. 2. Sodium bonding at quartz interface appeared intermittently. 3. Flared stainless steel tube, used to stop down annulus clearance, had no apparent effect on sodium wetting action. 4. Discoloration did not appear at sodium-to-quartz interface.
3 10/25/63	16'	Wall-0.050 OD-0.550	159	0.500	Hexane cleaned and outgassed 2 hrs at 1000°F	Evacuate to 25 μ . 270°F bottom and 650°F top temperature. No trace of oil condensate.	<ol style="list-style-type: none"> 1. Slight discoloration appeared where temperature reached 650°F. 2. Voids appeared along length of the rod, prior to helium backfill. 3. Helium back filling eliminated all void areas.

The following visual observations were made through the transparent quartz cladding:

- 1) UC fuel, subjected to oil during machining and subsequently degreased, reacted with sodium, causing bubbling during sodium pouring at 250 to 350°F. Such bubbling did not occur when the fuel was both degreased and vacuum outgassed, prior to bonding.
- 2) Complete filling of 16-ft rods, with sodium that was free of voids, could not be accomplished in a vacuum. However, if 1 atm (abs) He was admitted after filling, the sodium would be void-free.
- 3) Fuel rods which were without voids, at temperatures above the melting point of sodium while under 1 atm He, showed shrinkage voids upon sodium solidification.

C. SODIUM BONDING WITH SIMPLIFIED EQUIPMENT

Most of the fuel capsules fabricated for irradiation experiments at AI are Na or NaK bonded, by means of a fill tube in the upper end cap. Figure 3 shows such end caps, with their fill tubes. The capsule is heated, evacuated, and

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Figure 3. Composite End Cap and Fill Tube on Rods Fabricated by the Single-Rod Method

sodium is added through the fill tube, which is then pinched shut, and welded for final sealing. This fabrication technique, plus the ability to sodium-fill at low temperatures, as demonstrated in the quartz-tube experiments, was tested on full-length fuel rods.

The equipment designed for the quartz experiments, consisting of a low-temperature, air-atmosphere furnace, coupled with sodium apparatus from the 10-rod retort, was used to fabricate 14 experimental fuel rods by the capsule method. Four additional rods were fabricated in a conventional tube furnace, which was originally designed for reheating HNPF Core I fuel rods. The second furnace could accommodate fuel rods of up to 20 ft in length. Table VI lists the operational steps for making fuel rods, using the capsule or single-rod technique. Table VII summarizes the experiments performed. It should be noted that several of the failures were due to insufficient sodium in the fuel rod. Addition of the correct amount of sodium to the fuel rod (i. e. , obtaining correct sodium levels) was shown to be a somewhat different problem, in capsule type rods, than in retort fabricated rods.

The technique currently used for obtaining correct sodium levels in the bonding retorts involves filling the rod until sodium is visible, and then removing the excess through a suction tube. However, for the capsule or single-rod method, a previously developed eddy current sodium level detection device was used with moderate success. As shown in Table VI, sodium is poured more than once, with inert gas pressurization and re-evacuation between pouring operations. Although repetitive pouring was necessary to obtain the correct sodium level, repetition is feasible, in terms of time required; because the capsule system, unlike the bonding retorts, has a low volume, which fills and evacuates rapidly.

The equipment required for the described single-rod bonding method is relatively inexpensive, since standard commercial items can be used. However, several such pieces of equipment would be needed, to perform bonding in core-load quantities. Although neither time nor funding permitted full development of this technique for production use, the feasibility of the method was demonstrated.

TABLE VI

TYPICAL OPERATION FOR FABRICATION BY THE SINGLE-ROD PROCESS

Sequence	Operation	Temperature of Fuel Rod (°F)	Time	Atmosphere Inside Rod (Air outside at all times)	Description of Operation
1	Fuel loading	Ambient		Air	Fuel slugs manually inserted into stainless steel cladding. Bottom end closure welded and leak checked, prior to fuel loading.
2	Top end closure	Ambient		Air	Upper end cap welded into cladding with standard Heliarc welder and semiautomatic fixture which clamped and rotated fuel rod. Upper cap included fill tube, welded through cap prior to end closure welding.
3	Furnace loading	Ambient		Air	Fuel rod manually loaded into vertical, single-rod, air-atmosphere furnace. Open end of fill tube inserted into a vacuum seal at lower end of sodium-handling apparatus.
4	Heating and evacuation	Ambient to 300-500	2 hr	Air to 10 ⁻² torr vacuum	Rod evacuated through fill tube and heated simultaneously. Heating required 10 to 20 min, remainder of time at 300 to 500°F for continuation of evacuation.
5	Sodium filling	300-500	3 min	10 ⁻² torr vacuum	Sodium poured into rod until eddy current instrument indicated that preset level above fuel had been reached.
6	Pressurization	300-500	3 min	10 ⁻² torr vacuum to 1 atm He	Helium admitted through the fill tube into cladding space above sodium. Sodium level dropped a variable amount, 1/2 to 6 in.
7	Completion of sodium filling	300-500	10-15 min	Vacuum and He as needed	Rod evacuated to 10 ⁻¹ torr. Sodium again poured until desired preset level regained. Helium admitted, to 1 atm pressure. If sodium level changed significantly, fill cycle repeated a third time, until sodium level stable under pressure.
8	Cooling	300-500 to 150-200	30 min	1 atm He	Rod cooled in furnace.
9	Fill tube seal welding	Ambient	2 min	2 psia He	Fuel rod gas space evacuated to 2 psia. Fill tube pinched shut above upper end cap, using bolt cutter equipped with special jaws. Tube sheared immediately above pinch, and welded manually with standard Heliarc equipment.
10	Furnace unloading	Ambient		2 psia He	Rod manually removed from single-rod furnace.
11	Inspection	Ambient		2 psia He	Leak checking of final weld, visual inspection of cladding, and eddy current testing of sodium bond performed. Eddy current inspection made at 350°F.

TABLE VII
EXPERIMENTS IN SINGLE-ROD RETORT FURNACE TO DETERMINE SODIUM
BONDING CHARACTERISTICS OF UC FUEL TO TYPE 304 STAINLESS
STEEL CLADDING

Fuel Rod Sequence Number	Type 304 Stainless Steel Cladding		Fuel			Fuel Preparation Prior to Bonding	Vacuum, Heat, and Sodium Fill Statistics	Radac Eddy Current Trace and Visual Bond Results
	Length (ft)	Diameter (in.)	Length (in.)	Diameter (in.)	Weight (g)			
Run No. 1 — 12/5/62								
Rod OX	16	Wall-0.010 ID-0.540	159	0.500	Heat No. 333— 7,573.00	New cast UC fuel, degreased with trichlorethylene.	Vacuum of 0.1 μ maintained for 2 hr at 500°F, prior to sodium pouring. Backfilled with 50 psi He. Vacuum and fill tubes sealed off, leaving 3 in. Hg vacuum inside rod. Rod directionally cooled (bottom to top).	Cold trace indicated only part of fuel slugs were bonded, due to insufficient sodium level. A few shrinkage voids appeared where sodium was present, but dispersed during hot vibration testing. Visual inspection, after stripping, confirmed lack of sodium to cover top slug. Inside of rod appeared very clean, indicating consistent vacuum leak tightness
Run No. 2 — 12/18/62, 12/20/62								
Rod 002	16	Wall-0.010 ID-0.540	159	0.500		Fuel outgassed for 1 hr at 1000°F. Slugs stored in desiccator under 0.1 μ vacuum until start of test	Vacuum of 0.1 μ maintained for 2 hr at 500°F, prior to sodium pouring. Backfilled to 50 psi He, and rod directionally cooled to 150°F.	Cold traces of Rods No. 002 and 003, both cooled under 50 psi He, indicated a definite reduction of shrinkage voids at ends of rods. Center still contained large voids. Traces at 350°F showed shrinkage voids completely removed. Visual inspection, after stripping, revealed lack of gas space above fuel, indicating malfunction of sodium-level suction system.
Rod 003								
Run No. 5 — 1/3/63								
Rod 005	16	Wall-0.010 ID-0.540	159	0.500	Heat No. 351— 6,932.61	Fuel outgassed for 2 hr at 1000°F under 0.1 μ vacuum.	Vacuum of 0.1 μ maintained for 2 hr at 500°F, prior to sodium pouring. Rod completely sodium filled. Backfilled to 1 atm He. Directional cooling not utilized.	Traces at 70°F, 350°F, and after three hot vibration treatments indicated large unbonded areas, generally distributed throughout the rod. Visual examination verified validity of the trace indications. Trace charts, x-ray, and visual inspection confirmed sodium level to be at very top of rod.
Run No. 6 — 1/7/63								
Rod 006	16	Wall-0.010 ID-0.540	159	0.500	Heat No. 355— 6,924.50	Trichlorethylene degreased, but not outgassed.	Vacuum of 0.1 μ maintained for 2 hr at 500°F, prior to sodium pouring. Backfilled with 50 psi He after sodium pouring. Directional cooling not utilized.	Hot trace results of Rods No. 007 and 008 revealed large areas of inhomogeneities, scattered throughout entire rod lengths. These trace results compared with subsequent hot vibration trace results, indicating inhomogeneities primarily areas of lack of sodium bonding. These trace indications exceeded those of standard rod, therefore, these two rods considered rejectable. Rod No. 006 trace recordings showed no indications of inhomogeneities larger than 1/8 in. in diameter in the sodium annulus. Visual inspection proved the absence of sodium in top 1/3 section of Rods No. 007 and 008. Rod No. 006, which eddy current traces proved acceptable, also visually proved to be acceptable after stripping.
Rod 007					Heat No. 371— 6,839.27			
Rod 008					Heat No. 384— 6,764.32			
Run No. 7 — 1/11/63								
Rod 010	16	Wall-0.010 ID-0.540	159	0.500	Heat No. 381— 6,864.44	Trichlorethylene degreased, but not outgassed.	Vacuum of 0.1 μ maintained at 500°F for 2 hr, prior to sodium pouring. Backfilled to 50 psi He after sodium pouring. Directional cooling not utilized.	Results of hot eddy current sodium bond testing showed no trace indication of inhomogeneities larger than 1/8 in. in diameter in sodium annulus. The bond was acceptable.
Rod 011					Heat No. 364— 6,758.30			
Run No. 8 — 1/18/63								
Rod 012	16	Wall-0.010 ID-0.540	159	0.500	Heat No. 379— 6,955.15	Fuel was cleaned in butyl bromide, degreased, but not outgassed.	Vacuum of 0.1 μ held for 2 hr at 500°F, prior to sodium pouring. Backfilled with 50 psi He after pouring. Directional rod cooling not employed.	Trace patterns for Rods No. 013 and 014 met tentative specification requirements. Cold trace for Rod No. 012 indicated gross inhomogeneities in the sodium annulus, and withheld, pending results of hot vibration testing.
Rod 013					Heat No. 356— 6,889.30	Trichlorethylene degrease only.		
Rod 014					Heat No. 350— 6,836.00			
Run No. 9 — 1/21/63								
Rod 015	16	Wall-0.010 ID-0.540	159	0.500		Fuel for Rods No. 016 and 017 were trichlorethylene degreased. Fuel for Rod No. 015 was cleaned in butyl bromide. Fuel was not outgassed.	Vacuum of 0.1 μ held for 0.5 hr at 650°±50°F, prior to sodium pouring. Backfilled with 50 psi He, then cooled to 150°F. Rods were not directionally cooled.	Rod No. 017 met tentative eddy current specification requirements. Rods No. 015 and 016 withheld, pending results of hot vibration testing.
Rod 016								
Rod 017								

TABLE VII

**EXPERIMENTS IN SINGLE-ROD RETORT FURNACE TO DETERMINE SODIUM
BONDING CHARACTERISTICS OF UC FUEL TO TYPE 304 STAINLESS
STEEL CLADDING (CONTINUED)**

Fuel Rod Sequence Number	Type 304 Stainless Steel Cladding		Fuel			Fuel Preparation Prior to Bonding	Vacuum, Heat, and Sodium Fill Statistics	Radac Eddy Current Trace and Visual Bond Results
	Length (ft)	Diameter (in.)	Length (in.)	Diameter (in)	Weight (g)			
Run No. 1 — 2/5/63								
Rod 1X	17	Wall-0.010 ID-0.540	168	0.500	Heat No. 380—7,340.70	Fuel degreased with trichloroethylene.	1 μ vacuum pressure in retort at 350°F. Sodium level topped off 3-1/2 in. above fuel column. Back-filled with 50 psi He after sodium pouring. Directional cooling not applied.	Eddy current test revealed a few borderline inhomogeneities in the sodium annulus after hot vibration application. X-ray revealed sodium level to be 3-1/2 in. above fuel column.
Run No. 2 — 2/8/63								
Rod 2X	17	Wall-0.010 ID-0.540	168	0.500	Heat No. 385—7,288.65		Same as 1X. Sodium level topped off at 4-3/4 in. above fuel column.	Same as 1X. X-ray revealed sodium level to be 4-3/4 in. above fuel column.
Run No. 3 — 2/9/63								
Rod 3X	16	Wall-0.010 ID-0.540	168	0.500	Heat No. 372—7,206.53		Same as 1X. Sodium level topped off at 5-1/4 in. above fuel column.	Hot eddy current test revealed satisfactory bond. Sodium level 5-1/4 in. above fuel column.
Run No. 4 — 2/10/63								
Rod 4X	16	Wall-0.010 ID-0.540	168	0.500			Same as 1X. Sodium level topped off at 4-3/4 in. above fuel column.	Same as 3X, except x-ray revealed sodium level at 4-3/4 in. above fuel column

D. NONDESTRUCTIVE TESTS FOR THE SODIUM BOND

Eddy current testing, to determine sodium bond integrity with a Model 440 Radac machine, was the nondestructive method used for HNPF Core I U - 10 Mo fuel rods. Because of the similarity between these and the UC fuel rods, the same test method was adopted for the ESADA program. However, work was necessary, to determine: (1) whether the test results differed when UC, rather than U - 10 Mo, was used, and (2) whether significant cost reduction could be made.

The eddy current technique detects voids or inclusions in the sodium by indirectly measuring electrical conductivity. The coil consists of two windings: (1) a power winding which is fed high-frequency, 64 kc, current from an oscillator, and (2) a sensing coil, in which voltage is induced. The voltage induced in the sensing coil is a function of the eddy current losses from circulating current in the fuel rod. The Radac output is automatically graphed on a recorder chart which provides a permanent record of each inspection run.

Figure 4 pictures the test arrangement. The fuel rods are heated in a floor furnace. Each rod is lifted from the furnace through the Radac coil. The testing temperature is nominally 350°F. Since sodium melts at 207°F, the bond is always molten while being checked.

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Figure 4. Radac Eddy Current Machine for Nondestructive Testing of Sodium Bond in Full-Scale Fuel Rods

The reliability and sensitivity of the eddy current technique was tested in two ways. Experimental fuel rods which were eddy current tested were destructively examined, to compare the Radac chart recordings with defects observed in the cold rod when the cladding was removed. Eddy current tests were also performed on rods containing intentional built-in artificial defects. Artificial defects were used to determine and establish the reproducibility and sensitivity limits of the test method.

Tables II, III, and VII list the eddy current tests, as a part of the fuel rod data. Figure 5 shows a typical Radac chart with

A
END

B
END

76 10-5124

1) Prior to Loading Into Type 304 Stainless Steel Tube

76 10-5140 B

2) After Removal From Sodium-Filled Tube (arrows point to voids indicated by Radac traces in b-2)

a. Fuel Slug

1) "Hot" (300°F) Trace
(indicates three small
voids in sodium, which
are well within speci-
fication requirements)

2) Room Temperature
Trace (indicates sev-
eral small voids in
sodium, correspond-
ing to shrinkage voids
shown in a-2)

b. Eddy Current Traces

Figure 5. Fuel Slug and Corresponding Radac Bond Test Results

the corresponding sodium-covered fuel slug, immediately after the cladding was removed. As can be seen, the Radac test is very sensitive to defects, with high reliability; it always indicates a defect, and the size and shape of the indication on the chart repeats reasonably well. It will also be noted that the machine indicates not only defects in the sodium bond, but also fuel irregularities, such as slug ends and surface defects.

Sodium voids, as small as 1/16 in. in diameter, can be indicated on the Radac chart. The effective sensitivity, however, is a 1/8-in. diameter minimum void size, because of the inability to separate fuel irregularities from sodium voids on the Radac chart.

E. FUEL ELEMENT COMPONENTS AND FINAL ASSEMBLY

Two full-scale fuel element mockups were built to preliminary design drawings. The fabrication work on these early designs was done in parallel with additional design and analytical work; and information from experimental hardware fabrication, plus the analytical data, contributed to the final fuel element design.

Figure 6 shows the first fuel element mockup. The basic design concept of an 18-rod, bottom-supported, two-ring circular fuel cluster, embodied in this mockup, has been retained throughout the later work. Detailed features, not fixed in the first design, and which were subject to experiment during mockup fabrication, included: (1) the design of fuel rod spacers, (2) the design of the fuel rod end closure, and (3) the design of the lower support hardware.

1. Fuel Rod Spacers

The function of the spacer is to hold the fuel rods in a fixed geometry during reactor operation. The purpose of experimental work was to find the most economical configuration for manufacturing which would also meet functional requirements. This component (18 per element) was an important cost factor for each fuel element.

Many spacer designs were considered for the spacer. The design shown in Figure 7, with radial ribs Nicrobrazed to ferrules, was utilized in the first mockup. Its disadvantages were: (a) lack of strength, (b) insufficient bearing area against the process tube, and (c) difficult fixturing for brazing.

7610-5141C

a. Overall View

7610-5141D

b. Upper Hanger Assembly

7610-5142A

c. Lower Support Assembly

Figure 6. Full Scale Mockup Fuel Element

Figure 7. Fuel Rod Spacer for First Mockup Element

Figure 8. Fuel Rod Spacer for Second Mockup Element

Figure 9. Types of End Closure Welds Tested, and Test Specimen

Figure 10. End Closure Test Apparatus

The spacer configuration used in the final design used short tubing pieces, brazed together to form collars around each fuel rod. It had adequate strength, low weight and cross-sectional area, and employed simple tubular shapes.

Other designs which were considered and discarded because of functional defects, high cost, or both, were:

- a) Investment casting
- b) Welded or brazed honeycomb
- c) Spot welded wire lattice
- d) Tubular collars, dimpled to contact cladding at three points each, brazed or spot welded together (utilized in second ESADA mockup, Figure 8).

2. Fuel Rod End Closures

Both brazed and welded end closures were initially considered. Brazing was discarded in favor of welding, because of the large background of demonstrated operating reliability and fabrication experience with welded end closures in the SRE and HNPF.

A small test program was conducted, comparing several types of joints for welded end closures. The object of the testing was to evaluate various designs, from the standpoints of cost and reliability. The joints which were experimentally welded are shown in Figure 9. Five of each type were pressure loaded and thermal shock tested repeatedly. Internal pressure was increased, in increments of 100 psi, as thermal shocking proceeded. The thermal shock was created by heating to 1200°F and rapidly transferring the specimen to a water quenching bath. A diagram of the test equipment is shown in Figure 10.

Test data are presented in Table VIII. Photographs of failed specimens are presented in Figure 11.

F. CLEANING METHODS FOR FUEL SLUGS REMOVED FROM DEFECTIVE FUEL RODS

Because of the high value of the fuel, it is desirable that fuel slugs from defective fuel rods be reclaimed for rebonding in new cladding. The most obvious way to reduce cost is to minimize the fuel rod rejection rate. However,

TABLE VIII
END CLOSURE TEST DATA

Type Closure	Temperature (°F)	Pressure at Failure (psi)	Number of Temperature Cycles	Location of Failure
Conventional	1200	2000	20	Cladding
Conventional	1140	1500	5	Cladding
Conventional	1200	2000	20	Cladding
Conventional	1200	2000	27	Cladding
Conventional	1140	1700	24	Cladding
Cup Shape	1200	1900	27	End cap weld
Cup Shape	1200	1900	22	End cap weld
Cup Shape	1140	1700	26	End cap weld
Cup Shape	1200	1800	8	End cap weld
Cup Shape	1200	1800	24	Cladding
Shoulder	1200	1800	16	Cladding
Shoulder	1200	1800	37	Cladding
Shoulder	1200	2000	30	Cladding
Shoulder	1200	1800	19	Leak in cladding
Shoulder	1200	1900	23	Cladding

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a. Specimen No. 17 (Cup Shape) 22 Cycles (failed at 1200°F and 1900 psi)

7610-5170

b. Specimen No. 5 (Shoulder) 23 Cycles (failed at 1200°F and 1900 psi)

7610-5168

c. Specimen No. 8 (Conventional) 24 Cycles (failed at 1140°F and 1700 psi)

Figure 11. Failed Weld-Test Specimens

since some rejection must be expected, methods for practical and economical fuel recovery were investigated.

The Hallam U - 10 Mo fuel slugs were reclaimed by mechanical removal of cladding, followed by reaction of the bond sodium with butyl alcohol and then water. The mechanical cladding removal technique was refined to a high degree, during the Hallam work, and was used for the ESADA rods. The alcohol and water reactions were not applicable, however; since water reacts chemically with UC, causing decomposition of the fuel. The following alternate techniques were considered for the recovery of sodium-bonded UC slugs:

- 1) Sodium distillation
- 2) Slug transfer from defective cladding to new cladding in inert atmosphere without removal of sodium
- 3) Chemical cleaning, using:
 - a) Alcohol without water
 - b) Butyl bromide, followed by dimethylformamide
 - c) Ethylene glycol, followed by trichloroethylene vapor degreasing
 - d) Ethylene dibromide
 - e) Ethylene glycol n-monobutyl ether (Butyl "Cellosolve", produced by Chemicals Division of Union Carbide Corp.; or Dowanol-EB, produced by Dow Chemical Co.), followed by trichloroethylene vapor degreasing.

The method selected was the reaction of the fuel slugs with ethylene glycol n-monobutyl ether, followed by trichloroethylene vapor degreasing. The choice was based on quality of cleaning, material, labor and equipment costs, and the probability of fire or explosion in the reactants.

This method, now termed the Dowanol process, left no visible residue on the fuel; and chemical analysis showed no harmful trace elements, after cleaning. Fuel rods, bonded with fuel reclaimed in this manner, passed all tests required on production rods. Residual chlorine in the fuel slugs (from vapor degreasing) was found to be <5 ppm. The cost of the chief reagent, in commercial form (Dowanal EB or Butyl Cellosolve), is \$0.25/lb; which is about the same as the commonly used alcohols, and much less expensive than most of the other

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Figure 12. Ethylene Glycol n-Monobutyl Ether and Sodium Reaction

7610-5185

Figure 13. Cleaned Fuel Slugs

reagents considered. The reaction rate, which is moderately rapid, starts at ambient temperature, and does not require heating or temperature control apparatus. Trichloroethylene is also a low-cost material; and, since vapor degreasing is a well developed commercial process, equipment cost and processing time are also low. Ethylene glycol n-monobutyl ether has a flash point of 165°F. Since hydrogen is generated, during the sodium reaction, a hazardous situation could exist. However, by limiting reaction temperatures, and by proper ventilation, the problem was minimized. An open reaction tank with mating slug handling tray was designed, so that the temperature rise in the reagent never exceeded 130°F. The reaction operation was, in all cases, performed inside a hood with forced ventilation to remove hydrogen rapidly.

The procedure selected is outlined in Appendix A. Photographs of the equipment and fuel in-process are shown in Figures 12 and 13.

The following additional sodium removal methods were tried but were discarded for the reasons indicated:

- 1) Sodium distillation — Sodium oxide is not removed by distillation. The cost is high, because either long heating times, or complex equipment to reduce this time, are required.
- 2) Direct slug transfer from defective to new cladding — Feasibility was demonstrated, but labor and equipment costs are very high, because of necessity for a good inert atmosphere, to avoid an oxide coating on the bond sodium.
- 3) Chemical cleaning, using:
 - a) Alcohol without water — Insoluble reaction products remain on the fuel, and the operation could be hazardous.
 - b) Butyl bromide, followed by dimethylformamide — Special heated and cooled tanks are required, and the cost of the chemicals is high.
 - c) Ethylene glycol, followed by trichloroethylene vapor degreasing — The disadvantages are similar to those for butyl bromide; the reaction does not start below 80°C, and is difficult to control after it is started.

7610-51112

a. Container

7610-51112

b. Storage Rack

Figure 14. UC Fuel Handling and Storage Container

- d) Ethylene dibromide — The reaction is very slow, below the melting point of sodium.

G. UC HANDLING AND STORAGE

Cast uranium monocarbide fuel slugs are quite brittle, and can be broken and chipped during handling; they are also subject to decomposition, in the presence of water or moist air.

Early in the program, fuel slugs were transported between operating stations, and stored, in gallon-size metal containers with a desiccant. The containers were not hermetically sealed, and the slugs were free to move and chip during transportation. It soon became apparent that an improved container was needed, to reduce handling losses. The requirements for a good container are:

- 1) Provision for holding slugs in a fixed array, to minimize shock during handling
- 2) Provision for a desiccant, in each container, which is separated from the fuel slugs (saturated desiccant in contact with fuel will cause decomposition)
- 3) A quick lock cover which will hermetically seal reliably
- 4) A cover and container which will meet criticality requirements, and provide storage of adequate batch size
- 5) Simplicity of design, to minimize container cost.

A standard 5 in. in diameter by 10-1/2 in. high container, made to an Army-Navy specification, was chosen as the one which would best satisfy these requirements (See Figure 14). The cover of the can includes a V-groove clamping arrangement, with a rubber gasket for hermetical sealing. A removable storage rack, which accommodated sufficient slugs for one fuel rod, was designed for use with the containers; and these racks and containers were used for fuel handling during the demonstration production phase of the ESADA program.

The slug handling procedure used for loading of fuel into cladding tubes was similar to that used for the Hallam U - 10 Mo fuel rods. For the U - 10 Mo fuel, slugs were placed into tubes, inclined at 25° from the horizontal, and were allowed to slide to the bottom end of the rod. Because of the hardness and brittleness of UC slugs, however, slug breakage and scoring of the inner surface

of the stainless steel cladding frequently occurred. After trying several loading schemes, UC slugs were satisfactorily loaded with the cladding tube inclined at 15° , rather than 25° . The 15° angle was found to be such that slugs would not slide freely in the tubes, but moved so easily that little pressure was necessary to ease the fuel column along the inside of the tube.

III. DISCUSSION OF RESULTS – EXPERIMENTAL FABRICATION

A. SODIUM BONDING

1. Bonding Retort Temperature Cycle

The bonding cycle selected consisted of heating the fuel rods in the evacuated retort to 700°F, followed by reducing the temperature, and adding sodium at a rod temperature of 500°F. Bonding can be accomplished at both higher and lower temperatures. At higher temperatures, longer heating times are required, and sodium vaporization is increased. Bonding at lower temperatures was demonstrated, using the single-rod technique; but the design of the 60-rod retort was such that, at temperatures much below 500°F, the temperature gradient along the length of the rod was too great; and in some cases, sodium near the top of the rod solidified.

Insufficient experiments were conducted to establish a minimum time for the 700°F segment of the 700 to 500°F temperature cycle. The experimental data, however, confirmed by the bonding yields during the Phase II element demonstration work, indicated that no more than 2 hr at 700°F is necessary.

The optimum bonding temperature cycle, with the existing batch type vacuum furnace equipment, consists of heating to 700°F for a maximum of 2 hr, followed by sodium filling at 500°F.

2. Fuel Preparation for Bonding

It was established that satisfactory bonding is possible, without outgassing or degreasing the fuel slugs prior to loading them into the cladding. The highest yields were obtained, using the 700 to 500°F bonding cycle, and using fuel without preparatory treatment, other than dry end machining.

3. Bonding Mechanism—Quartz-Tube Experiments

The visual observation of bonding in quartz tubes, coupled with data from the conventional bonding equipment, provided a reasonably accurate picture of the detailed events which occur during sodium filling of fuel rods.

The following conclusions were reached:

- a) Sodium does not wet the fuel rod annulus during filling of the rod. Wetting is not necessary. The annulus can be filled, free of gas bubbles of significant size (1/8 in. or larger), without wetting.

- b) Complete filling of the annulus does not occur until a gas pressure (1 atm of helium is used) is applied to the sodium in the rod.
- c) Satisfactory sodium filling of the fuel rod can be accomplished at rod temperatures as low as 300°F. Higher temperatures are used, in existing production equipment, because of existing equipment limitations and the reduction of evacuation times at higher temperatures.
- d) The indicated pressure (5 μ or better), used in the bonding retort during sodium filling, is not indicative of gas pressure inside the fuel rod annulus. It was found experimentally that the gas pressure in the fuel rod annulus is in the order of 50 to 200 μ when filling starts, and that rods can be satisfactorily bonded under these conditions. Attainment of a pressure of 5 μ in the fuel rod annulus requires 20 to 40 hr of evacuation time, and is not necessary.
- e) Violent evolution of gases during sodium pouring will occur if oil-contaminated UC slugs are not vacuum outgassed, prior to fuel rod loading. Fuel slugs which are not exposed to oil, and which are protected from similar contaminants, are satisfactorily bonded without prior vacuum outgassing or other cleaning operation.

4. Single-Rod Fabrication Method

The eighteen rods, fabricated by this method, were sufficient to demonstrate the feasibility of the process, and to establish that satisfactory fuel rods can be manufactured, using this technique.

The following is a list of advantages and disadvantages of the single-rod method, compared to the selected method of fabricating large batches of rods in a vacuum bonding furnace:

a. Advantages

- 1) The required equipment is inexpensive, most of it being commercially available.
- 2) Maintenance is easy, because of standardization and the ease of stocking commercial spare parts. Failure of any one part in the 60-rod bonding retort may shut down the entire bonding

operation, while failure of one part in a series of single-rod bonding furnaces affects only a fraction of the total production capacity.

- 3) End closure welding is simplified in the single rod process, because it can be done in air, using established techniques, and because it is done prior to filling the rod with sodium. Welding of the upper end closure is the largest single cause of rod rejection, when using the 60-rod bonding retort, because the welding must be done remotely, and in the same atmosphere for sodium handling.
- 4) The single-rod technique is very flexible. Changes in fuel rod diameter, overall length, fuel length, and gas space length can be accommodated with simple tooling adjustments. Corresponding changes in the large vacuum furnace batch technique require major tool redesign and/or equipment modification, in most cases.
- 5) Production rates and product quality appear to be less dependent upon operator skill, because both the equipment and the process are simpler and less specialized.
- 6) The process appears to be adaptable to high production, semi-automated techniques.
- 7) Fuel rods can easily be produced with any desired internal gas pressure. The batch type vacuum retort system allows only pressure near 1 atm, because end closure welding must be performed at the pressure which is retained in the rod.

b. Disadvantages

- 1) Economy and adequate production rates are predicted upon a short fabrication cycle of 1 hr or less, per fuel rod. Such a cycle is technically feasible, with one possible exception: adequate evacuation of the fuel rod, to obtain a satisfactory bond, may require more than 1 hr. If so, separate pre-evacuation of the fuel rod, prior to entry into the bonding furnace, will be necessary. This area requires further investigation.

- 2) Smaller and simpler sodium systems, such as a feasible manifold system, are in order. Further development is required in this area.

The flexibility and probable economy of the single-rod system would seem to justify further work.

5. Eddy Current Nondestructive Testing

Eddy current testing was proven to be a satisfactory method for detecting voids as small as 1/8 in. in diameter in sodium bonded UC fuel rods.

B. FUEL ELEMENT COMPONENTS AND ASSEMBLY

1. Fuel Rod Spacers

The final design uses a series of short tubes, brazed together to form the spacer. This design represented a considerable improvement over the previous ones considered. Insufficient effort was expended on spacer design, and this area is one in which cost reductions could be realized.

2. Fuel Rod End Closures

The test data showed the cup shaped end closure to be inferior, in that failure often occurred in the weld zone, rather than in the cladding. The hollow end cap tended to increase the stress on the weld, and this type of closure also presented problems of fuel rod support at the bottom hardware. Holes for locking pins, or grooves for snap rings, cannot be as readily formed as in a solid end cap which protrudes from the cladding.

The test data showed the shoulder type end closure to be equivalent to the conventional closures in strength. Although the shoulder type end cap is similar and cheaper to manufacture, it is more difficult to locate properly in the cladding for welding. Since no justification was found for changing the conventional welding lip design used for both the HNPF and SRE cores, this design was also used for ESADA. The main components of a fuel rod (end caps, slug, and cladding) are shown in Figure 15.

Figure 15. Components of ESADA Fuel Rod

7610-5111

TABLE IX

DEMONSTRATION FUEL ROD PRODUCTION YIELDS

Run Number	Number of Rods Processed	Number of Acceptable Rods	Yield of Acceptable Rods (%)	Rejections			
				Poor Welds	Cladding Damage	Lack of Bond or Irregular Fuel Column	Incorrect Sodium Level
1	60	33	55	19	5	3	0
2	59	38	64.4	16	4	1	0
3	58	47	81.1	5	4	2	0
4	60	51	85.0	8	1	0	0
5	59	56	95.0	3	0	0	0
6	60	55	91.6	3	2	0	0
7	60	59	98.3	0	1	0	0
8	57	54	94.7	1	2	0	0
Total	473	393	83.3	55	19	6	0

IV. DISCUSSION OF RESULTS - DEMONSTRATION FABRICATION

A. FUEL ROD FABRICATION EFFORT

The overall yield for the fuel rod fabrication effort was 83.3%. However, from Table IX, it can be seen that the yields for the last 4 of the 8 loads ranged from 91.6 to 98.3%, averaging 94.9%.

Table IX indicates that most rejections in the initial batches were due to defective upper end cap closure welds. Efforts were made to find the causes for these defects, which had not been encountered in any of the shakedown or experimental trials. By repairing the welding equipment, cleaning the weld area more thoroughly, improving the fit between the end cap and the cladding, and increasing the welding amperage, immediate yield increases resulted. Appendix B contains a detailed description of the fuel rod fabrication process.

B. SPACER MANUFACTURE

The brazed spacer design, as pictured in Figure 16, was the one chosen for the Phase II production run demonstration elements. As shown, the spacer consisted of various sizes of thin-walled, Type 304 stainless steel tube sections,

7610-51121

Figure 16. Fuel Element Bottom Support Fuel Rod Spacers

surrounded by an outer band; all surfaces in contact were brazed together. The larger diameter tubes, containing the fuel rods, were heavier in wall thickness than the smaller diameter interstitial tubes. The main purpose of the interstitial tubes was to assure the required rod spacing, without undue restriction of the sodium coolant flow.

Prior to furnace brazing the assembled spacers, the individual tubular components were cut to length and plated with the nickel alloy brazant. The thickness of the plating was 0.0005 in. The design of the spacer was such that the various size tubes could be push fitted into position during assembly; special tooling, consisting of solid pins machined to close tolerances and oriented to simulate fuel rod positions, was used during the assembly operation. The actual brazing was accomplished by heating at $1840 \pm 50^{\circ}\text{F}$ for 20 min in a hydrogen atmosphere furnace.

The technique of preplating the components with the brazing material not only assured sound joints, but facilitated the assembly and brazing operations. The sectioning and plating of the various sized spacer tubes were subcontracted, while the assembly and brazing was done in-house.

Prior to the start of this fabrication process, prices ranging from \$59 to \$88, and from \$217 to \$283, for each fuel rod spacer and each fuel element bottom support spacer, respectively, were obtained from outside vendors for various designs. Since such costs were prohibitive, the spacers were redesigned, and again the prices quoted by outside vendors were prohibitive. It was then decided to fabricate the spacers at AI, using the previously described fabrication procedure. Each fuel rod spacer and bottom support spacer was produced for \$34.50 and \$144.92 respectively. The overall yield on the assembly and brazing of spacers was 96%.

It should be pointed out that the unexpected high vendor quotations, plus the necessary redesigning efforts, had not only delayed completion of the program by 3 to 4 weeks, but clearly illustrated that insufficient design time had been devoted to this unanticipated problem.

Sufficient hardware, including tubing for the spacer components, was purchased to complete the assembly of 20 full-scale elements. The spacer tubes were sectioned by one contractor, plated by another, and then returned to AI for assembly and brazing, along with the remaining portions of tubing which were

not sectioned. After approximately 200 spacers (enough for assembling 13 fuel elements) had been fabricated, it became apparent that a shortage of one size of sectioned tube pieces would prevent fabrication of the additional spacers needed to complete the assembly of 7 additional fuel elements, for a total of 20 elements. In reviewing the situation, there were two possible alternatives: (1) from a remaining length of this particular size tubing, additional sections could be cut, sent out for plating, and then returned to AI for assembly and brazing, or (2) assemble 13, instead of 20, elements, although there were sufficient fuel rods and other hardware for 20 elements.

Despite the fact that the program had already been delayed, because of spacer problems described previously, the first alternative was chosen. This meant that completion of the program would be delayed another 2 to 3 weeks, because of outside supplier scheduling for plating requirements, plus the fact that the in-house spacer brazing and element assembly operations, having been terminated after the 13 elements were completed, would have to be restarted.

C. FUEL ELEMENT ASSEMBLY

A total of 22 full-scale, 18-rod, sodium-bonded UC fuel elements were assembled during the program. Two elements, of varying spacer and end cap design, were assembled during the development phase (Phase I). The remaining elements, using the fixed reference design, were assembled during the demonstration phase (Phase II). The following is a discussion of the assembly of these latter fuel elements.

While the spacers were being fabricated, the other components of the fuel elements (the bottom housing and shaft subassembly, shown in Figures 17 and 18, and the actuator rod and top subassembly, shown in Figure 19), were assembled. Positioning of the spacers onto the central support tube was simplified, by use of a specially designed tooling fixture which automatically positioned, and properly oriented, the spacers every 12 in. along the length of the support tube. While so positioned, the spacers were permanently TIG^{*} spot welded to the support tube. With the spacers in place, the preassembled actuator rod was assembled to the center support tube, by inserting the actuator rod (thread first)

*Tungsten Inert Gas

7610-51116

Figure 17. Bottom Housing Components

7610-51101

Figure 18. Bottom Assembly
for Fuel Element

Figure 19. Top Assembly
for Fuel Element

7610-51197

Figure 20. Full-Scale ESADA Fuel Element

through the bottom end of the tube and threading a hex nut onto the top end of the actuator rod to hold it in place. The housing on the shaft subassembly was then secured to the support rod, by wiring them together with stainless steel wire. At this point, the entire assembly was stored in a below-floor-level storage area. With the assembled components in this position, fuel rods were vertically loaded into the fuel element center tube and spacer assembly. Individual fuel rods were removed from shipping containers, positioned at a near vertical angle, by means of an overhead crane. The rods were lifted and positioned, and then threaded through the spacer tubes. This procedure was repeated until the entire bundle of 18 fuel rods was completed. When loading of the rods was completed, the entire element was raised, and the bottom end caps of the fuel rods were wire locked together. After lowering the element back into the storage hole, the guide assembly was assembled to the support rod, and the knob was assembled to the actuator rod. The final step consisted of wire locking together all of the hex nuts with 0.030-in. diameter stainless steel wire, as shown in Figure 19. The finished element is shown in Figure 20. A more detailed description of the fuel element assembly procedure is given in Appendix C.

The accuracy with which the spacers were fabricated, positioned, and oriented permitted self threading or guiding of the fuel rods through all spacers.

The overall fuel element assembly procedure was simple and efficient, and proceeded without difficulty. An assembly rate of 2 elements/day, with three men, or approximately 200/year, was expected; however, there was no difficulty in producing 4 elements/day with the same number of people.

V. CONCLUSIONS AND RECOMMENDATIONS

This program clearly demonstrated that the processes developed, and described in this report, are economically feasible for the production of high-quality, sodium-bonded, stainless steel clad, uranium carbide fuel elements.

The major cost components for the fabrication of the Phase II full-scale fuel elements were as follows:

- a) Fuel Rod Fabrication
- b) Fuel Element Component Hardware
- c) Fuel Element Assembly

Improvements could be made in fuel rod fabrication techniques, so as to increase yields and efficiency. It is possible to eliminate some of the end cap welding problems encountered early in the program, by employing improved automatic welding devices. These devices do not require as much operator skill; however, some redesign of the present retort would be required.

The use of induction heating, rather than of electric furnace heating, of fuel rods for sodium-bond eddy current inspection has merit. The induction coil could be mounted in tandem with the eddy current coil, and heating and inspection could be performed simultaneously, as the rod travels through the coils. This would eliminate the 15 to 20 min heating time required with the present furnace.

The use of the single-rod retort method for sodium bonding, described in the developmental portion of this report, may offer additional cost reduction.

Further cost reductions are possible with improved tooling for fuel rod and element fabrication. An example is the fuel rod spacer; it is estimated that, with additional design, tooling, and increased quantity, the cost could be reduced significantly. As indicated during fuel element assembly operations, it should also be possible to assemble 6 to 8 elements/day, with very minor design changes.

APPENDIX A
BUTYL CELLOSOLVE - TRICHLOROETHYLENE PROCEDURE
FOR RECOVERY OF FUEL FROM DEFECTIVE FUEL RODS

A. APPARATUS

The stainless steel tank is 14 by 14 by 4 in. deep. A wire tray, made of 1/8 in. steel rods spaced 3/8 in. apart, fits snugly into the tank and keeps the slugs approximately 1/2 in. above the bottom of the tank. A basket handle, about 5 in. high, is an integral part of the tray.

The tray carrier is made of 1/2 in. steel strips, of such size that the wire tray fits into the carrier. The handle is about 2 ft high; so that the apparatus may be easily transported, and also suspended conveniently in a trichloroethylene degreasing tank.

The trichloroethylene tank is about 3 by 5 by 5 ft tall, with a roll-back cover. The liquid is heated, so that the vapor rises about halfway up the tank.

B. OPERATION

The stainless steel cladding of the fuel element is removed by a roll-stripping process, and the sodium-bonded slugs are transferred to the wire tray, which is placed on a table. The slugs are allowed to stand until the bright sodium color has darkened. The tray and contents are then placed in the tank, and Butyl Cellosolve is poured to a level 1/2-in. above the slugs. Hydrogen is evolved, and the action continues for about 12 min, accompanied by a temperature rise of approximately 15°C. Each slug is then rotated 180°, and is examined for residual sodium (cracked slugs require more reaction time). The liquid is drained, and the tray and slugs are moved to Tank No. 2, containing clean Butyl Cellosolve. The tray is dipped and raised several times, drained, and moved to Tank No. 3, where this operation is repeated.

The tray and contents are placed in the tray carrier and immersed, as soon as possible, in trichloroethylene vapor for 30 to 60 min. The slugs are removed from the carrier and placed in a vacuum desiccator at about 100°C, to remove the last traces of any trichloroethylene decomposition products, after which the temperature is raised to 1000°F for approximately 1 hr. The slugs are cooled to room temperature under vacuum, wrapped in aluminum foil, and stored in airtight cans containing a desiccant.

Figure 21. ESADA Fuel Rod Fabrication Process Flow Diagram

APPENDIX B

ESADA FUEL ROD FABRICATION PROCESS DESCRIPTION

Figure 21 is a flow diagram of the ESADA fuel rod fabrication process.

A. RECEIVING AND PREPARING COMPONENTS FOR FABRICATION

1. Cladding

The cladding was Type 304 stainless steel tubing, 0.550-in. ID by 0.010-in. wall by $180.75 \pm 1/4$ in. long. As received, tubing was contained in a paper sleeve with plastic end caps over the ends, to maintain cleanliness. The cladding was packaged in rigid wooden containers, and was handled with clean, lint-free gloves at all times.

The cladding was prepared for use by removing the paper sleeve, inspecting the surface, and then placing it in the handling susan, which had plastic pipes to contain and support the entire length of the cladding.

The plastic end caps were retained on both ends of the cladding until it was necessary to remove them.

2. End Plugs

The end plugs were machined, from Type 304 stainless steel, to AI drawings 7610-703609, -4 (bottom), and -3 (top) (See Figure 15). A plastic dip was used to protect the weld lip, as well as the end which fitted into the cladding.

Prior to use, enough stock was machined from the end cap to make a snug fit with the representative ID of each mill lot of tubing. The plugs were cleaned in acetone, handled with clean, lint-free gloves, and stored in a clean, cushioned, covered pan.

3. Fuel Slugs (Specification NB0177-007)

The fuel slugs, when received from the vault, were packed in hermetically sealed containers. The fuel, as received, was already machined, pre-batched into fuel rods (140.00 ± 0.50 in.), and packaged according to the ESADA Fuel Batching Procedure (Section 3, Paragraph 2).

7543-5135

Figure 22. Welding Bottom End Plug

7543-18 14

Figure 23. Helium Filling

B. WELDING BOTTOM END PLUG CLOSURE

After the paper sleeve was removed from the cladding and the inspection was completed, 60 tubes were loaded into the lazy susan handling fixture, which was then lined up in back of the welding fixture. The plastic cap was removed from one end of the cladding, and the bottom end plug was inserted in the cladding and checked for snug fit. The welding lip was butted firmly against the end of the cladding. The cladding and bottom end plug were then positioned in the welding fixture and Heliarc welded (Figure 22).

The welding parameters are given in the following table:

WELDING PARAMETERS

Speed (rpm)	2 (approx.)
Current (amp)	35 to 50
Cladding exposure above chill block (in.)	0.090 (approx.) (visual, while cladding rotating)
Inspection	Dimensional — Go-No-Go gauge
Maximum diameter (in.)	0.580
Maximum TIR (in.)	0.020

The closure was helium leak checked by Quality Control personnel. A vacuum line was fastened over the bottom end, where the weld closure had been made, and helium was injected into the tube through the plastic cap on the top end of the cladding (Figure 23). Detection of helium was an indication of a leak in the weld. A Veeco Model MS-9AB mass spectrometer leak tester, with a sensitivity of 10^{-10} cc/sec, was employed.

C. LOADING THE CLADDING

1. Transfer of Tubes to Retort Susan

After bottom end cap welding and inspection, the cladding was cleaned, to remove dirt and grease, by means of an acetone wipe. The tubes were then manually loaded into the lazy susan, while the susan was horizontal. A Teflon guide was used to prevent cladding scratches. The retort susan was then moved to the pit area, and positioned at a 15° incline, for the loading of UC slugs.

Figure 24. Loading Fuel Into Cladding

7543-5140

a. Components

7543-1805

b. Assembled

7543-1806

Figure 25. Upper End Plug Closure

2. Batching Fuel Slugs

The fuel was prebatched and packaged into cans, according to the following fuel batching procedure: Machined, inspected, and identified (by heat number) slugs were batched into the correct fuel length column of $140 \pm 1/2$ in. For preservation, they were packaged into hermetically sealed containers (one fuel rod per container). Within each container was a rack to protect the slugs from damage (Figure 14b). Attached to the lid of each container was a packet of silica gel desiccant. Each container had a card attached, showing the heat number, a summary of the weights of the individual heats within the batch, and an inspector's verification stamp.

3. Loading Fuel Slugs

A clean, stainless steel sleeve (flared at one end) was inserted into the end of the cladding, to assist in the loading operation. The fuel slugs were loaded, and their rod positions recorded on an accountability form.

When a batch (containing $140 \pm 1/2$ in. of fuel slugs) was loaded into the cladding tube, the position and length of each slug was recorded. The slugs were carefully pushed to the opposite end of the cladding with a stainless steel push rod. The rod position in the retort susan was recorded. This loading operation was witnessed by an inspector (Figure 24). Accountability records were rechecked for accuracy and completeness, before the retort susan was placed into the retort.

4. Upper End Plug Closure

A collet was used to secure the gear to the cladding (Figure 25). A gauge was used to space the end of the cladding 0.090 in. from the top of the collet. The end plugs were machined to fit each lot of cladding with a slight interference fit. The end plugs were inserted into the retort through an air lock, after the sodium was poured.

D. SODIUM BONDING AND SEALING

1. Retort Loading

The retort susan was lowered into the retort by means of a crane (Figure 26). Prior to insertion, stainless funnels were placed into the end of each cladding tube in the retort susan.

7543-1803A

Figure 26. Lowering Retort Susan into Retort

2. Pre-operational Check of Retort

Before the retort was sealed for the start of the bonding cycle, a check was made of the operation of all equipment, as well as of all parts and tools required for the bonding cycle. These checks were compared against a check-off list.

3. Retort Evacuation

The retort cover was lowered into position and secured. All glove port covers, valves, etc., necessary for proper evacuation, were readied. The retort was evacuated to a pressure no greater than 0.5 μ .

4. Sodium Filling

After the evacuation had reduced the retort pressure below 50 μ , and the temperature of the retort had stabilized at 700°F, the sodium pour pot was heated to approximately 375°F. After at least 2 hr at temperature, and a retort pressure no greater than 0.5 μ for at least 1-1/2 hr, sodium pouring was begun. The lazy susan was rotated, to position a rod under the Na pour tube. The rod was then completely filled with sodium. This operation was repeated until all 60 rods were filled.

5. Sodium Bond Sampling

When all the fuel rods were filled with sodium, the retort was filled with helium to atmospheric pressure, and held for 2 hr. The retort was then cooled to 350°F. Sodium sample containers were lowered into the fuel rods, and a sample was withdrawn by manipulating the sample containers by means of the retort gloves. The sample containers were then removed from the rods, and the oxide content of the sodium was determined. Maximum allowable oxide content was 400 ppm.

6. Removing Excess Sodium

The suction pot was heated to a temperature of between 300 and 400°F. The pot and tube assembly was rotated until the suction tube was above the most convenient fuel rod. The suction tube was then lowered into the fuel rod until it rested on a fixed stop on the retort cover. At this position, the suction tube was approximately 2-1/2 in. above the top of the fuel, and the excess sodium was siphoned out. The suction tube was then lifted out of the fuel rod and repositioned over the next fuel rod. The operation was repeated for the remaining 59 fuel rods.

7. Upper End Plug Welding

The retort power was turned off, and the retort was cooled to ambient temperature. The fuel rod upper end plugs were cleaned in acetone, and were inserted into the retort through the air lock. The plugs were firmly seated in the cladding. The retort susan was rotated until the gear on the first fuel rod engaged the drive gear mounted on the retort cover. The welding head was then adjusted, vertically and rotationally, until the electrode was in position for welding. The fuel rod was rotated, using a drive motor mounted on the retort cover. A magnetic clutch was engaged, to start the rod rotating. The end plug was welded in accordance with Atomics International Weld Specification NA 0312-004. This operation was repeated for the remaining fuel rods.

8. Retort Unloading and Equipment Servicing

The retort cover was removed from the retort by means of the crane, and was placed on its special stand. After several retort loads (~ 8 to 10), the sodium pot was removed, disassembled, and steam cleaned. The sodium filter within the pot was replaced. After every second retort load, the sodium pour pot was refilled. After every retort load, the sodium suction pot was replaced with a clean unit.

The retort susan, and the retort vessel itself, were cleaned of all sodium spill, etc.

E. INSPECTION AND CHECKING

1. Fuel Rod Identification

Identification numbers were electroetched on the upper end plugs, before the fuel rods were removed from the retort susan. These identification numbers consisted of the retort susan hole number, etched on the end of the upper end plug, and the retort batch number, etched on its shank.

2. Upper End Plug Closure Leak Check

The upper end plug-to-cladding joint was helium leak tested, as required by Atomics International Weld Specification NA 0312-004. Helium had been sealed into the fuel rods, as a result of helium back-filling before the welding of the upper end plug closure. Fuel rods having leaks were rejected. After the leak check was completed, the fuel rods were transferred to carrying cans, and were moved to the hot eddy current test station.

3. Hot Eddy Current and X-Ray Tests

The hot eddy current test was used to inspect the fuel rods for voids in the sodium. Allowable voids were specified in AI Product Specification 7610-18-001, and the test procedure, as outlined in "Radac Eddy Current Inspection for Sodium Bonding in ESADA Fuel Rods," Laboratory Instruction No. QA33. Rods containing voids larger than were allowed were vibrated and re-inspected. The sodium level in the fuel rods was determined by means of x-ray, using Polaroid film (Figure 27). The rods were then returned to a 120-rod lazy susan storage rack for cooling.

4. Dimensional Inspection

The fuel rod was inspected dimensionally, in accordance with Fuel Rod Drawing 7610-703609 and AI Product Specification 7519-18-001.

5. Surface Inspection and Packing

The surface of the fuel rod cladding was visually inspected for scratches and dents, using a 5X magnifier, in accordance with Product Specification 7610-18-001. This visual inspection was the last operation performed before the fuel rods were packed into the shipping containers (Figure 28). Packing was done in accordance with AI Specification NA0312-005, "ESADA Fuel Rods, Cleaning, Shipping, Storage."

6. Fuel Slug Rework

Fuel slugs were reclaimed from rejected fuel rods by stripping the cladding from the rods and removing the sodium from the slugs in a solution of Dowanol-EB, as described in Section II-F.

After dissolving the sodium through a series of room-temperature Dowanol-EB baths, the fuel was subjected to trichloroethylene vapor degreasing, followed by vacuum outgassing at room temperature, to remove residual trichloroethylene vapors.

After the cleaning, the slugs were rebatched and rebonded as soon as possible.

Figure 27. Preparing to X-ray
Sodium Level

7543-1808

Figure 28. Fuel Rods in
Shipping Container

7610-51107

APPENDIX C

ESADA FUEL ELEMENT AND ASSEMBLY DESCRIPTION

Figure 29 is a flow diagram of the ESADA fuel element assembly process.

A. ASSEMBLY OF ACTUATOR ROD

The Actuator Rod (7610-703614-4) was assembled by welding the threaded rod (-5 top) and the knob (-7 and -8 assembly, bottom) to the stainless steel tube (-6) which had been cut to length (183.38 in.). One of these actuator rods was required per element.

B. HOUSING AND SHAFT ASSEMBLY

The housing (7610-70364) and shaft (7610-703615-3) was assembled by assembling the link and dog (7610-703615-4 and -5) to the shaft and securing in place with a dowel pin (7610-703608-6). This pin was then tack welded in place. The springs (7610-703615-10 and -11) were inserted into the housing assembly, the shaft installed, and the dogs were positioned and tack welded in three places. The components are shown in Figure 17.

C. ASSEMBLY OF ACTUATOR ROD (7610-703614-4) TO THE HOUSING AND SHAFT ASSEMBLY (7610-703615-3)

The Actuator Rod was inserted into the housing and shaft, and the holes were lined up. A pin (7610-703615-7) was inserted into the hole. A 1/16-in. diameter hole was drilled through the pin, and a cotter pin (7610-703615-12) was installed.

D. ASSEMBLY OF SUPPORT ROD AND FUEL ROD SPACERS (7610-703616-4)

The support rod, with the top support (7610-703610-3) and bottom guide (-4) welded in place, was positioned on the assembly fixture (7610-703618). The spacers (15, 7610-703620 and 1, 7610-703619) were threaded onto the support rod, and spaced 12 in. apart. Each spacer contained a groove in the center ring, which was engaged upon a rectangular pin attached to each spacer locating block within the fixture. With the spacers automatically positioned and oriented in the proper plane, the extended portion of the center spacer ring was Heliarc spot welded to the support tube (2 places, 180° apart).

Figure 29. ESADA Fuel Element Assembly Process Flow Diagram

E. ATTACHING HOUSING AND SHAFT, AND ACTUATOR ROD TO THE SUPPORT TUBE AND SPACERS

With the spacers in place, the actuator rod (subassembly) (7610-703614-4, Step 1) was attached to the center support tube by inserting the actuator rod, thread first through the bottom end of the support tube. A hex nut was installed onto the threaded top portion of the actuator rod, to hold it in place. Two half-moon shaped segments (7610-703615-6) were used to position the housing and shaft assembly to the bottom of the support rod, and all were lock wired in place with 0.030-in. diameter stainless steel wire (Figure 18).

Note: The assembly was now ready to be loaded with fuel rods.

F. POSITIONING ELEMENT FOR LOADING FUEL RODS

The assembly was inserted vertically into the fuel loading and storage rack. The storage rack consisted of corrugated steel pipes, bundled together and inserted into a large floor hole. Each corrugated pipe contained one fuel element.

G. LOADING FUEL RODS

The shipping container was positioned at an angle of approximately 10° from the vertical. By means of an overhead crane and a special hook, one fuel rod at a time was removed from the container, positioned directly over one of the top spacer holes, and lowered through the spacers into the element. The spacers were aligned with such accuracy that the fuel rod guided itself from one spacer to the other. This procedure was repeated until the entire bundle of 18 fuel rods per element (six in the inner row, and 12 in the outer row) was loaded.

H. LOCK WIRING OF FUEL RODS

The inner row of fuel rods was always loaded first. As each row was loaded, the entire element was lifted, by crane, out of the storage; and the bottom end caps of the fuel rods were lock wired together, by threading 0.050 in. stainless steel wire through a hole in the stem of the end cap.

I. ASSEMBLY OF GUIDE ASSEMBLY

After the fuel rods had been lock wired together and lowered back into the storage hole, the guide assembly (7610-703613) and knob (7610-703616-3) were

assembled at the top. Hex nuts were used to position the knob in the proper position, and all parts were lock wired together with 0.030-in. diameter stainless steel wire (Figure 19). The element, at this stage, was completely assembled (Figure 20).