URANIUM ALLOY FUEL ELEMENT
FABRICATION DEVELOPMENT
FOR HNPf CORE I

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ABSTRACT

A fuel element, consisting of a cluster of stainless steel clad, sodium bonded, U 10 wt % Mo fuel rods, has been proposed for the first core loading in the Hallam Nuclear Power Facility.

Analytical data on density, soundness, chemical composition, dimensions, and surface finish were obtained from more than 100 heats of fuel slugs which were vacuum cast in graphite molds. The quality levels obtained were satisfactory, and casting was proven to be a feasible fabrication method for U 10 wt % Mo fuel slugs.

Extrusion and liquid pouring were both investigated as methods of handling sodium to bond fuel rods. The extrusion technique was shown to be impractical, because of difficulty in supplying a sufficient volume of sodium to fill the rod. Satisfactory bonding was obtained, using the liquid technique.

Two full-scale fuel element mockups were fabricated. Each element contained 19 fuel rods, located by spacers made from spot welded strips, and enclosed in a process tube. Assembly problems encountered in the first mockup were corrected by modifying the fuel rod spacers. Methods were developed for safe handling of the fuel rods and other long (15 ft) components. The second mockup demonstrated that the fuel element was suitable for fabrication and assembly.

Physical testing was performed on fuel rod end closures, cladding support springs, the variable orifice thermocouple, and the fuel rod spacers. The end closures and support springs were shown to have adequate strength. The thermocouple functioned well at temperatures and flexure conditions simulating reactor operation. A minimum material thickness was determined for the fuel rod spacers.

I. INTRODUCTION

A. BACKGROUND

The fuel element design concepts and fabrication techniques for Hallam Nuclear Power Facility (HNPF) Core I emanated from Sodium Reactor Experiment (SRE) experience. Of necessity, HNPF development was concentrated in the area of greatest difference between Hallam and SRE fuel elements.* The chief differences are:

- 1) Fuel alloy - HNPF will use U - 10 wt % Mo, instead of the pure U and Th-U used in SRE Cores I and II.
- 2) Fuel-to-cladding bond - HNPF will use a Na bond, rather than the NaK used in SRE fuel rods.
- 3) Core size - The Hallam fuel elements will be twice as long and the core will contain three times as many elements as SRE Core I.

The U - 10 wt % Mo alloy slug is relatively difficult to fabricate by wrought methods. This fact, together with favorable development information available on the casting of U - Mo alloys,¹ pointed to casting as the fabrication method for fuel for HNPF Core I.

Sodium was chosen as the fuel bonding material, in order to utilize its excellent thermal conductivity. Na is approximately 2.5 times better than NaK, in this respect. The conductivity improvement is accompanied by higher specific power and consequently a smaller core.

A secondary advantage of Na is the easier handling and shipping of fuel rods. Na has significant ambient temperature strength, reinforcing the thin wall

*The terms fuel rod, fuel cluster, and fuel element do not have the same meaning to all engineers. For purposes of this report, they are defined as follows:

Fuel Rod - One length of cladding, containing fuel slugs and bonding material, with plugs welded to form closures on both ends.

Fuel Cluster - A group of fuel rods, joined together with fuel rod spacers plus hangers at both ends.

Fuel Element - A fuel cluster, enclosed in a process tube and joined to end hardware, a guide at the bottom, and a disconnect joint at the top. A shield plug, hanger rod, and variable orifice are not considered part of the fuel element.

cladding against handling damage and preventing fuel slugs from shifting within the cladding during transportation.

From a fabrication standpoint, the most important difference between Na and NaK is their melting points. NaK, which melts at 12°F, was poured at ambient temperature into SRE rods in vacuum to bond the fuel.² Na must be heated above 207°F to obtain fluidity for bonding. The heating requirement, plus the 15-ft length of the Hallam rods, demanded development of new equipment and techniques.

A program on a UO_2 fuel element concept preceded the U alloy program described in this report. The UO_2 work was terminated in favor of a U alloy fuel before development was complete; however, some of the early fabrication development for oxide fuel was applicable to elements utilizing metallic fuel. In particular, it became apparent that there were fabrication problems directly related to the length and quantity of fuel rods in the cluster.

A full-scale (15 ft long fuel rods) 19-rod oxide mockup was built, embodying SRE structural design features.³ Specifically, a spiral wire wrap on alternate cladding tubes set minimum rod spacing, and the only structural support for the rods was hangers at both ends. The assembled element was so flexible that rod spacing was highly variable, and handling during fabrication and core loading was shown to be completely impractical.

Longitudinal rigidity was incorporated into the design by enclosing the cluster in a large tube, termed the process tube. For neutron economy, Zircaloy 2 was chosen as the process tube material.

Heat transfer studies for HNPF Core I elements showed that nonuniform spacing of the 19 rods was necessary, to obtain a reasonably flat temperature profile across the cluster. Wire wrap on the rods is compatible only with uniform spacing. Therefore, to mechanically accomplish accurate nonuniform spacing, a system of spacers, made from thin strip material and placed at intervals along the cluster length, was devised.

In this manner, the basic structural design concept for HNPF Core I was evolved before fabrication development on U-Mo fuel elements started. Consequently, the development of U-Mo fuel element hardware was centered on determining the feasibility of and refining the spacer-process tube configuration.

A size comparison of SRE Core I and the proposed HNPF Core I follows:

Core	Fuel Rod Length (ft)	Fuel Rods per Fuel Element	Fuel Elements per Core Loading	Fuel Rods per Core Loading
SRE I	8	7	42	294
HNPF I	15	18	151	2718

The large number of fuel rods planned for HNPF Core I placed emphasis on economy and scheduling. Fabrication development, particularly Na bonding, had to be aimed at techniques applicable to large batches and short process cycles. It was largely economy considerations which led to a Na bonding retort designed for multiple fuel rods and for flexibility in bonding techniques.

B. OBJECTIVES

The objectives of the program were to:

- 1) Develop and demonstrate casting, as a fabrication method for U-Mo fuel slugs.
- 2) Develop equipment and techniques for Na bonding of full-length fuel elements.
- 3) Fabricate full-scale mockups, to demonstrate the feasibility and economy of various designs.
- 4) Test fuel element components on which performance is closely linked to fabrication techniques.

II. FUEL SLUG FABRICATION

A. EXPERIMENTAL CASTING

Several heats were poured, to obtain slugs for destructive analysis and experimental heat treatment. In addition, a large amount of process and analytical information was obtained, in collaboration with other HNPF fuel programs (e.g., pre-irradiation data from MTR and SRE irradiation experiments, and information from fuel for physics experiments,⁴ was combined with data generated directly on this program). Table I lists the U 10 wt % Mo castings fabricated for all HNPF programs.

The casting technique used is reported in detail in References 1 and 4. Briefly, the technique was as follows: Vacuum induction melting and casting was done in machined graphite crucibles and molds. The mold cavities were coated with a magnesium zirconate mold wash. Pouring temperatures were between 1390 and 1420°C, at a maximum pressure of 200 μ . Residual mold material was removed by shot blasting, and slug ends were machined to finished lengths on a lathe. Cast slugs and graphite molds are shown in Figure 1.

Figure 1. Graphite Molds and Cast U 10 wt % Mo Fuel Slugs

TABLE I
SUMMARY OF U 10 wt % Mo FUEL SLUG CASTING AND ANALYTICAL DATA

Purpose of Slugs	No. of Slugs Cast	Nominal Slug Size (in.)	Dimensions				Density		Chemistry			
			Diameter		Straightness				Mo Content		Carbon Content	
			Range of Variation (in.)	No. of Slugs Measured	Max. Deviation from Straight Line (in.)	No. of Slugs Measured	Range of Variation (g/cc)	No. of Samples Measured	Range of Variation (wt % Mo)	No. of Samples Measured	Range of Variation (ppm)	No. of Samples Measured
Physics Experiments	3850	0.590 diam. x 12 long	± 0.005	3850	0.005 as-cast 0.015 gamma homogenized	3850 12	16.90 to 17.25*	600	9.6 to 10.6	600	310 to 1100†	600
MTR Irradiation	130	0.505 diam. x 2 long	± 0.005	130	Not applicable	Not Applicable	17.16 to 17.28	72	9.8 to 10.3	18	600 to 840	12
SRE Irradiation	100	0.590 diam. x 6 long	± 0.005	67	0.004 as-cast	36	17.15 to 17.33	100	9.9 to 10.6	24	370 to 650	48
Analysis	10	0.630 diam. x 11.6 long	± 0.003	10	0.005 as-cast	3	17.12 to 17.22	10				
Analysis	10	0.630 diam. x 10.1 long	± 0.003	10	0.005 as-cast	10	17.10 to 17.27	10				

*Of 91 heats accepted for experimental use, only one heat showed a density below 17.00 g/cc.

† Of 91 heats accepted for experimental use, the three heats with the most carbon showed contents of 900 to 1100, 860 to 900, and 760 to 840 ppm. All other heats were below 810 ppm.

The largest molds that were successfully used contained ninety slugs, each 0.590 in. in diameter and 12 in. long.

B. EXPERIMENTAL HEAT TREATMENT

The scope of this fabrication program did not include the selection of the heat treatment for Core I fuel. Since the irradiation studies of U 10 wt % Mo fuel on other programs have not proceeded to the point of determining the optimum microstructure, methods were investigated for both homogenization and transformation of cast U 10 wt % Mo fuel slugs.

Heat treatment for gamma homogenization was performed at several time and temperature combinations, listed in Table II. Two specimens were heat treated for each combination. The specimens were 0.75 in. in diameter by 1 in. long. A typical homogenized microstructure is shown in Figure 2.

Various heat treatments were also investigated for gamma transformation to α plus γ' . Three specimens, 0.59 in. in diameter by 1 in. long, were transformed at each time and temperature shown in Table III. Figure 3 shows the microstructure of a fully transformed specimen.

All heat treatment was done with the fuel slugs enclosed in evacuated quartz tubes.

C. RESULTS

A summary of the analytical results is included in Table I. More detail on the analysis of fuel for physics experiments is available in Reference 4. The theoretical maximum density of U 10 wt % Mo is in the range between 17.1 and 17.3 g/cc, the exact value depending on the microstructure of the material.

Surface finishes, measured with a profilometer on shot blasted slugs, were in the range between 60 and 230 rms. A high percentage of all slugs cast showed no detectable internal porosity under radiographic inspection (gamma source). For example, only 6% of 4110 fuel slugs for physics experiments were rejected for all types of defects, including unsoundness.

The grain sizes resulting from various homogenization treatments are included in Table II. Metallographic results indicated the maximum temperature and minimum time for homogenization is 1000°C and 8 hr. This condition produced a gamma structure without excessive grain growth.

TABLE II

CAST U 10 wt % Mo GAMMA HOMOGENIZATION
HEAT TREATMENT EXPERIMENTS

Gamma Heat-Treat Conditions		ASTM Grain Size
Time (hr)	Temperature (°C)	
32	800	4
24	800	4
32	850	3 - 4
24	850	4
28	900	2
24	900	4
20	900	3
16	900	3 - 4
24	950	3
20	950	2 - 3
16	950	3 - 4
8	950	4
20	1000	> 1
16	1000	> 1
8	1000	2 - 3
As-cast	-	1 - 2

Specimen Size - 0.75 in. diam x 1 in. long. All heat treatment was in vacuum. Cooling was in vacuum outside the furnace.

150X

Figure 2. Gamma Homogenized U 10 wt % Mo, Vacuum Heat Treated 30 hr at 850°C

Figure 3. Transformed U 10 wt % Mo, Vacuum Heat Treated 24 hr at 900°C, Cooled, and Vacuum Treated for 250 hr at 475°C

100X

TABLE III

CAST U 10 wt % Mo GAMMA TRANSFORMATION TO ALPHA PLUS GAMMA
PRIME HEAT TREATMENT EXPERIMENTS

Transformation Conditions		Transformation (%)	Room Temperature Electrical Resistivity ($\mu\Omega\text{cm}$)	ASTM Grain Size
Time (hr)	Temperature ($^{\circ}\text{C}$)			
150	450	20	63.5 ± 3.2	<u>2</u> * - 3
150	475	40	54.5 ± 4.6	2 - <u>3</u>
150	500	70	58.1 ± 3.9	2 - <u>3</u>
250	450	55	53.9 ± 4.2	3 - <u>4</u>
250	475	95	52.5 ± 3.8	3
250	500	95	49.0 ± 1.9	4 - <u>5</u>
350	450	60	-	3 - <u>4</u>
350	475	95 - 100	-	2 - <u>3</u>
350	500	95 - 100	-	4 - <u>5</u>
As-cast	-	-	-	<u>1</u> - 2

* indicates predominant grain size

Specimen size - 0.59 in. diam x 1 in. long. All heat treatment was in vacuum. Cooling was in vacuum, outside the furnace. All specimens were gamma homogenized, previous to treatments listed in this table.

Table III shows the percentage transformed at different times and temperatures. The degree of transformation was measured metallographically. Electrical resistivity measurements did not correlate well with the metallographic results. High contact resistance between the specimens and the electrodes used for resistivity measurement caused the inaccuracy. The effect of contact resistance could be reduced by increasing specimen length between contact points.

III. SODIUM BONDING OF FUEL RODS

A. EQUIPMENT

Since both the size of the fuel rods and the bonding process were unique, it was necessary to develop special equipment. Experience with the retort for NaK bonding of 8-ft SRE fuel rods was used as a basis for equipment design.²

1. Equipment Requirements

The fuel rod fabrication equipment had to provide:

- a) A heat source, to elevate fuel rod temperature to 800°F, in either vacuum or inert atmosphere, with selective control for directional cooling.
- b) Means of inserting Na in the fuel rods.
- c) Apparatus to weld fuel rod end closures, after bonding, without exposing the Na to air.
- d) Glove box operation, at ambient temperatures and under inert atmosphere, to allow manual access to the fuel rods and internal mechanisms.
- e) Flexibility to accommodate different fuel rod lengths and diameters and various bonding techniques.

2. Retort Design

The basic features of the retort are shown in Figures 4 and 5. Heating is provided by tubular resistance heaters with 25 kw of electrical power. The heaters are divided into six zones, with a separate control for each zone. The evacuation system is capable of maintaining a vacuum of less than 1μ at ambient temperature. Argon and dry helium* are supplied to the vessel through manual valves.

The airlock permits the insertion of tools and spare parts into the retort under inert atmosphere, thereby preventing the exposure of a full load of fuel rods to air due to a minor equipment malfunction. A rack, termed the "lazy susan", inside the vessel holds ten fuel rods in a circular array. The entire

* Helium dried by bubbling through NaK.

Figure 4. Diagram of Retort for Na Bonding and Welding End Closures on Fuel Rods

Figure 5. Retort for Na Bonding and End Closure Welding of Fuel Rods

lazy susan rotates to index each fuel rod into position for end closure welding and sodium filling. By means of a variable speed drive motor, each fuel rod can be individually rotated for welding. The rod is driven, instead of the welding head, to allow clearance for various end plug sizes and for thermocouple leads in instrumented fuel rods.

A flanged opening was provided for the vacuum-tight mounting of any desired sodium handling devices. An enlarged section was provided in the vessel, near the upper end of the lazy susan, for the mounting of sodium level instrumentation.

3. Sodium Handling Equipment

An extrusion cylinder was built with suitable flanges for mounting on the side of the retort. It was hydraulically driven with a hand pump. The cylinder and hydraulic system are illustrated in Figure 6 a and b. The cylinder was loaded by removing it from the retort and inserting brick sodium into the flanged end. The extrusion hole was in an insert plate, so that the extrusion diameter could be changed easily.

Figure 7 illustrates the apparatus which was built for the handling of liquid sodium. The pot, valve, and pour tube are separately heated and thermocoupled. The valve is an all stainless steel unit with poppet-type action. A bellows seal is used on the stem, instead of a packing gland, to provide a positive seal against air leakage into the filtered sodium. The filter screws into the bottom of the pot and can be removed for cleaning. Helium pressure is used to force sodium through the filter. The inverted cup over the filter prevents helium from blowing through the filter until the Na level reaches the bottom of the cup.

B. BONDING BY EXTRUSION

Both APDA and ANL have reported methods for sodium bonding fuel rods by the extrusion method. It should be noted that their fuel rods were smaller, in both length and sodium annulus, than the HNPF Core I rods.

The experimental bonding by the extrusion method did not lead to a practical technique for HNPF fuel rods. The procedures outlined in the following section indicate the limitations of the method.

Figure 6a. Components of Na Extrusion Cylinder

Figure 6b. Na Extrusion Cylinder Assembled with Hydraulic Ram and Pump

Figure 7. Liquid Handling Apparatus for Na

Figure 8. Flow Diagram for Fuel Rod Fabrication

1. Experimental Bonding

Figure 8 shows a flow diagram for fuel rod fabrication. A typical bonding cycle in the retort is shown in Table IV. The experimental bonding trials are summarized in Table V. Some of the early work was done, in the 21-rod SRE retort, with less than full length rods.

Complete wetting of some fuel slugs (never all the slugs in a rod) was observed in several of the early experimental rods, but it was difficult to produce proper conditions for wetting over the entire rod length. Because of an insufficient volume of sodium to fill the annulus, slugs near the upper end of the cladding were consistently unbonded.

Two difficulties were encountered in introducing the correct volume of Na into the rod:

- a) The volume of the annulus (6.15 in.^3) was greater than the volume of the empty cladding above the fuel (5.6 in.^3). Thus, it was impossible to put enough solid sodium inside the cladding to fill the annulus.

TABLE IV

TYPICAL CYCLE IN RETORT FOR Na BONDING BY THE EXTRUSION METHOD

Sequence	Operation	Temperature (Retort Walls) (°F)	Time (hr)	Atmosphere in Retort	Procedure
1	Rod Loading	Ambient	2, for full load of 10 rods	Air	Load fuel rods into the retort lazy susan with a crane. Rods, at this point, have bottom end closures welded, top ends open, and dry fuel slugs inside. Tighten the chill blocks on the rods; put hand tools, springs, and end caps into the retort; and put the cover onto the retort.
2	Inert Gas Filling	Ambient	1	Vacuum, then He	Evacuate the retort to a maximum pressure of 1μ . Fill the retort with dry He to a pressure of 1 atm.
3	Na Extrusion	Ambient	3	He	Extrude Na into the retort. Manually, using the gloves, cut Na bars into measured lengths. Insert the bars of Na into the upper ends of the fuel rods above the fuel.
4*	Heating	Ambient to 1000	6	Vacuum	Turn on all heaters and start evacuation simultaneously.
5	Bonding	1000	12	He	Fill the retort with a pressure of 1 atm of dry He when wall temperature reaches 1000°F. Set the automatic temperature control for 1000°F.
6*	Directional Cooling	1000 to Ambient	34	He	Turn off heat on Retort Zones 4, 5, and 6. (Heated zones are numbered 1 through 6. Zone 1 is at the upper end, and 6 is at the bottom). After 4 hr, turn off Zone 3. After another 4 hr, turn off Zone 2. Manually turn power on and off, on Zone 1, to maintain a difference of 300°F between Zones 1 and 2 until Zone 2 has cooled below 200°F.
7†	Na Level Determination	Ambient	?	He	Measure the Na level in each rod with an inductive instrument or a manual dipstick. Add or subtract Na from each rod, as needed. If Na is added, repeat the heating sequence (Steps 4, 5, and 6).
8	End Closure Welding	Ambient	3	80% He 20% A	Manually, using the gloves, insert the springs into the upper end of each rod. Insert the upper end caps into each rod end. Evacuate to a pressure of 24 in. of He. Fill to a pressure of 1 atm with argon. Manually adjust the welding head to bring the electrode into welding position. Start the rod drive motor and weld the first rod. Index to the next rod and repeat the welding procedure until all end closures are welded.
9	Rod Unloading	Ambient	1	Air	Remove the retort cover. Remove chill blocks from rods. Lift the completed fuel rods out of the retort with the crane.

*If extruded Na is put into the rods in two separate loads, heating and cooling, Steps 4 and 6, must be performed twice.

†Step 7 was not included in the experimental work. Bonding by extrusion was abandoned before this refinement was reached.

TABLE V

Na BONDING BY EXTRUSION - TRIAL SUMMARY

Test No.	Fuel			Cladding		Annulus Size (Radial) (in.)	Number of Rods in Retort	Equipment	Bonding Cycle			Results	Comments
	(Fuel material: Cast normal U - 10 wt % Mo)			(0.010 in. Wall Type 304 Stainless Steel)					Na Insertion Method	Temperature (Retort wall) (°F)	Time at Temperature (hr)		
	Diam (in.)	Length in Rod (in.)	Surface Condition	Outside Diam (in.)	Length (ft)								
1	0.565	39	Machined and Shot Blasted	0.625	4.0	0.020	2	21-Rod SRE Retort	Manually cut from brick in retort and put on top of fuel	700	6	Cyclographing indicated voids in the bond. Decanning showed randomly distributed irregularly shaped voids in bond on all slugs. Cyclograph chart correlated well with actual bond. More than 80% of slug surfaces wet.	On all experimental bonding, the retort wall temperature given is an average of various areas of the retort wall. The poor bond was due to insufficient temperature and time.
2	0.565	39	Machined and Shot Blasted	0.625	4.0	0.020	2	21-Rod SRE Retort	Manually cut from brick in retort and put on top of fuel	700	2	Cyclographing showed very erratic bond. Decanning showed less than 25% wetting.	Delay in starting heating cut short the time at max. temperature. Very poor bond tended to confirm importance of time and temperature.
3	0.565	48	Machined and Shot Blasted	0.625	8.0	0.020	2	21-Rod SRE Retort	Manually cut from brick in retort and put on top of fuel	700	6	Cyclographing showed voids in bond on both rods. Decanning one rod verified cyclograph inspection.	One rod was reheated to 800°F in an air atmosphere for 8 hr and directionally cooled by lowering out of furnace at 2 ft/hr. Destructive examination showed complete bonding.
4	0.590	132	Shot Blasted	0.650	15.0	0.020	2	10-Rod HNPf Bonding Retort	Extruded Na put on top of fuel	800	8	13 out of 22 slugs in 2 rods combined were completely bonded. Most of the poor bonding was near upper end of rods.	18 in. diam top window on retort cracked at elevated temperature, admitting air to the retort. There were several inches of Na ₂ O at the top end of each rod.
5	0.590	162	Shot Blasted	0.650	15.0	0.020	10	10-Rod HNPf Bonding Retort	Extruded Na put on top of fuel in gas space and 7 in. above cladding	1000	16	End plugs could not be welded because of zinc and Na on cladding ends. Bonding results not significant.	Brass sleeves for fuel rods in retort hot zone dezincified. Upper Na and cladding ends were contaminated with zinc.
6	0.590	162	Shot Blasted	0.650	15.0	0.020	10	10-Rod HNPf Bonding Retort	Extruded Na loaded under top two fuel slugs	700	2	Na was ejected from cladding at a mean retort wall temperature of 500°F. Two rods destructively examined showed bonding on 70% of slugs. Slugs at top and bottom were unbonded.	Time and temperature were low because of a cooling water leak in adjacent equipment, causing shutdown.
7	0.590	162	Shot Blasted	0.650	15.0	0.020	10	10-Rod HNPf Bonding Retort	Extruded Na put on top of fuel in gas space and 9 in. above cladding	800	3	Extruded bar Na above cladding toppled onto retort floor instead of going into cladding. There was no bond inspection, but there could not have been sufficient Na for complete bonding.	
8	0.590	162	Shot Blasted	0.650	15.0	0.020	2	10-Rod HNPf Bonding Retort	Extruded Na put on top slugs twice, with heating after each addition	800	19	Insufficient Na was present to bond upper 40 in. All other slugs bonded except bottom 20 in.	7.5 in. ³ of Na was added. By calculation, this was a sufficient volume. The calculation omitted volume between slug ends and the effect of cladding which was above diameter tolerance limit.

NAA-SR-5291

- b) The volume of the annulus can vary, from one fuel rod to another, by about $\pm 20\%$, due to the cumulative variations in fuel and cladding diameters (0.590 ± 0.005 in. fuel slug diameter and 0.630 ± 0.003 in. cladding inside diameter).

Consequently, the minimum sodium volume required to insure a complete bond was increased to 7.4 in.^3 ($6.15 \text{ in.}^3 + 20\%$).

Several modifications of the basic procedure (Table IV) were tried, in an attempt to overcome the volume problem.

- a) The sodium bar was allowed to protrude above the top of the cladding, to provide additional volume of extruded sodium. Sodium was successfully melted into the annulus in this manner, but traces of sodium remained on the open cladding end after heating. Sodium vaporized in the arc and caused blowholes in the end closure weld.
- b) A sleeve with a funnel-shaped end was placed inside the top end of the cladding to protect the cladding end from sodium contamination (See Figure 9). However, the thickness of the sleeve walls subtracted

Figure 9. Introduction of Extruded Na into the Fuel Rod, Using a Funnel-and-Sleeve Guide Inside Cladding

from the diameter available inside the cladding, so the length of extruded Na above the cladding was increased to maintain sufficient volume. With 9 in. of sodium above the cladding, the heating of the rods caused the sodium bars to fall onto the retort floor, rather than slide into the cladding, thereby requiring extensive cleaning of the vessel. Therefore, this modification was shown to be impractical.

- c) The third experimental modification in technique involved the removal of fuel slugs from the loaded cladding to make room for sodium. The two upper fuel slugs were loaded into the cladding in the retort after the extruded sodium was in the fuel rod. In this manner, it was possible to leave a fuel slug protruding at the top, rather than

sodium. During the heating of fuel rods so loaded, sodium was violently ejected from the cladding. The exact mechanism of ejection is unknown, but it probably involved the plugging of the cladding tube with sodium.

- d) Finally, the introduction of the extruded sodium in two separate loads was tried. The empty cladding space was filled with sodium and the rod was heated until melting occurred. At this point, wetting temperatures were not necessary. Only enough heat was used to make the sodium fluid. The retort was cooled and a second load of sodium was placed in the cladding. The second heating cycle was conducted at a 800°F wall temperature for 12 hr, in the normal fashion, to achieve complete wetting. Because of an error in the sodium addition, complete bonding was not obtained. The double cycle technique, however, appeared to be feasible if properly executed. There was no problem with sodium spills and end plug welding was possible.

During most of the experimental bonding by extrusion, the extrusion cylinder was loaded with brick sodium in air. The surfaces of the bricks, as loaded, were heavily oxidized. Sodium bars extruded into the dry helium atmosphere of the retort had bright silvery surfaces which appeared to be oxide free. When these bars were examined by cutting sections, however, visible particles of oxide were found.

Loading of the extrusion cylinder in a drybox, separate from the bonding retort, was tried. It was a cumbersome, lengthy process, and did not produce any major improvement in the purity of the extruded Na.

2. Discussion of Results

The only feasible technique found for Na bonding by extrusion, the double-heating method, was uneconomical, in terms of cycle time. It was found that the first heating and cooling sequence involved almost as much time as the final one, because internal retort temperatures at the upper end of the fuel rod lagged several hundred degrees behind retort wall temperatures during heating. Thus, the double-heating cycle added at least one 8-hr work day to the time for each retort load.

A proposed increase in the Na annulus from 0.020 in. to 0.025 in. would increase the Na volume required per fuel rod to 9 in.³. This volume is near the upper limit for the quantity which can be added by the double-heating method. If it were necessary to add sodium to each rod in three separate batches, the bonding cycle would become even longer, and the method would be completely impractical.

Other techniques for extrusion bonding were considered and discarded without trial.

These techniques were:

- a) Placing the sodium in the bottom of the fuel rod and putting the fuel on top of it.
- b) Using sleeves above the upper end of the cladding to support protruding bars of extruded sodium.
- c) Extruding directly into hot fuel rods in a vacuum, preheating the sodium as it leaves the extrusion cylinder.

Techniques (a) and (b) would add considerably to equipment cost and/or cycle time. Technique (c) is so similar to the liquid handling method that it appeared more practical to convert to a fully heated system and gain the advantage of a filter.

The high oxide content of the extruded bars was unsatisfactory. Improvement would probably have been possible, with specially designed inert atmosphere loading equipment for the extrusion cylinder. However, there was reasonable doubt that satisfactory purity could be obtained unless the extrusion cylinder were filled from a heated pot, allowing filtering and cold trapping. Obviously, if a heated system is used, it is simpler to eliminate extrusion and pour directly into the fuel rods.

C. BONDING BY LIQUID HANDLING

1. Experimental Bonding

The experimental bonding trials are summarized in Table VI. A typical bonding cycle in the retort is shown in Table VII.

The first liquid bonding results were very similar to those obtained by extrusion bonding. That is, the bottom half or two-thirds of the fuel was

TABLE VI

Na BONDING BY LIQUID HANDLING - TRIAL SUMMARY

Test No.	Fuel			Cladding		Annulus Size (radial) (in.)	Number of Rods in Retort	Equipment	Bonding Cycle					Time at Bonding Temperature (hr) and Mode of Cooling	Results and Comments
	(Fuel Material: Cast normal U - 10 wt % Mo)			(0.010 Wall, Type 304 Stainless Steel)					Na Temperature in Liquid Apparatus (°F)			Retort Wall Temperature During Na Pouring (°F)	Retort Wall Temperature During Bonding (°F)		
	Diam. (in.)	Length in Rod (ft)	Surface Condition	OD (in.)	Length (ft)				Pot	Valve	Pour Tube				
1			No fuel. This trial was a test of the Na apparatus only				None	10-rod HNPF Bonding Retort	400	505	310 to 520	Ambient		Valve and filter operated satisfactorily when Na was poured into a pan inside the retort. 17 in. of pressure across filter produced Na flow.	
2	0.590	162	Shot blasted and pickled with 48% nitric 2% hydrofluoric acid solution	0.650	15.0	0.020	1	10-rod HNPF Bonding Retort	540	430	320 to 430	900	900	Heaters shut off after Na pouring. Cooled to ambient temperature in 26 hr.	Cladding gas space was filled with Na to top of cladding. Lower 70 in. of fuel bonded. Upper slugs were unbonded in irregular spots.
3	0.590	162	Half of slugs shot blasted only. Others were blasted and pickled in 50 g/l of chromic acid in concentrated sulphuric acid.	0.650	15.0	0.020	1	10-rod HNPF Bonding Retort	400	400	280 to 420	725	1000	17, Heaters turned off bottom first in 24-hr period.	Fuel in lower 120 in. bonded completely. A linear void ran the length of upper 42 in. of slugs on one side. No difference was seen in bonding on blasted slugs, opposed to blasted and pickled slugs.
4	0.590	162	Shot blasted	0.650	15.0	0.020	1	10-rod HNPF Bonding Retort	620	440	350 to 450	700	No Bonding		With 2 atm of He pressure across the filter, only a few drops of Na came from the pour tube. Examination of apparatus after cooling showed that the pour tube was plugged, close to the valve.
5	0.560 to 0.580	162	Swaged, extensive cracking in surfaces.	0.650	15.0	0.025 to 0.035	2	10-rod HNPF Bonding Retort	350	400	200 to 350	800	1050	8, Heaters turned off bottom first in 34-hr period.	One rod was completely bonded. The second rod was completely bonded, except for a 0.2 in. ² area, 30 in. from the bottom end.

TABLE VII

TYPICAL CYCLE IN RETORT FOR Na BONDING BY THE LIQUID HANDLING METHOD

Sequence	Operation	Temperature (Retort Walls) (°F)	Time (hr)	Atmosphere in Retort	Procedure
1	Rod Loading	Ambient	2, for full load of 10 rods	Air	Load fuel rods into the retort lazy susan with a crane. Rods, at this point, have bottom end closures welded, top ends open, and dry fuel slugs inside. Insert sleeves into the upper end of each fuel rod. The sleeves touch the top fuel slugs and have funnels at their upper ends. Tighten the chill blocks on the rods; put hand tools, springs, and end caps into the retort; and put the cover onto the retort.
2	Heating	Ambient to 800	4	Vacuum	Turn on all retort heaters and start evacuation simultaneously. Turn on heaters on pot, valve, and pour tube in the Na pouring apparatus.
3	Na Pouring	800	1	Vacuum	Index a fuel rod to a position directly under the pour tube. With the pot at 300°F, valve at 400°F, and pour tube at 300 to 400°F, open the valve and let Na run into the tube until the Na level instrument indicates Na above the upper fuel slug. Index to the next fuel rod and repeat the pouring operation until all rods are Na filled.
4	Bonding	1000	12	He	Fill the retort with dry He to a pressure of 1 atm. Heat the retort walls from 800°F to 1000°F and hold with automatic temperature control.
5	Directional Cooling	1000 to 200	30	He	Turn off heat on Retort Zones 4, 5, and 6. (Heated zones are numbered 1 through 6. Zone 1 is at the upper end, and 6 is at the bottom). After 4 hr, turn off Zone 3. After another 4 hr, turn off Zone 2. Manually turn power on and off on Zone 1 to maintain a difference of 300°F between Zones 1 and 2 until Zone 2 has cooled below 200°F.
6	Na Level Determination	200	2	He	Twist and remove each sleeve from the upper ends of the fuel rods. Turn on heater Zone 1 at intervals during this operation if the Na becomes too stiff to allow sleeve removal.
7	End Closure Welding	Ambient	3	80% He 20% A	Manually, using the gloves, insert the springs into the upper end of each rod. Insert the upper end caps into each rod end. Evacuate to a pressure of 24 in. of He. Fill to a pressure of 1 atm with argon. Manually adjust the welding head to bring the electrode into welding position. Start the rod drive motor and weld the first rod. Index to the next rod and repeat the welding procedure until all end closures are welded.
8	Rod Unloading	Ambient	1	Air	Remove the retort cover. Remove chill blocks from rods. Lift the completed fuel rods out of the retort with the crane.

completely bonded, but the slugs near the top had voids in the bond in random locations. The empty cladding above the fuel was filled with sodium.

A later experimental trial produced the same results, with one exception. The void in the bond was a continuous channel along the upper 45 in. of fuel. Examination of the sodium slug above the fuel revealed a corresponding linear void through the center of the Na for its entire length. The linear void was very similar to the shrink hole commonly seen in the gates of castings or in the tops of ingots.

The banks of retort heaters were turned off progressively from the bottom to the top, over a period of 24 hr, during this experimental run, in an attempt to obtain directional solidification. The shrinkage at the top of the annulus suggests that, because of radiant heat losses from the cladding upper end to the cool upper chamber of the retort, directional solidification in the proper direction (bottom first) did not occur at the top of the rod.

For the final experiment (Test No. 5, Table VI), several steps were taken to improve directional cooling. A large mass of steel, in the form of heavy wall tubing around the lazy susan central post, was added at the upper end of the retort to provide heat during retort cooling. The liquid Na was poured to a level 4 to 6 in. above the upper fuel slug in the fuel rod. Filling to higher levels in earlier experiments contributed to rapid cooling of the cladding upper end by providing a heat conduction path through the excess Na. The upper end of the retort was heated intermittently for 12 hr after the lower 13 ft of the vessel started to cool.

Test No. 5 produced essentially complete bonding over the entire fuel length in two fuel rods. There were no shrinkage voids, and wetting was complete, with the exception of a 0.2 in.² area, 30 in. from the bottom of one rod.

During all the experiments, the intended operating temperatures for the liquid Na apparatus were 300 to 350°F for the pot, 400 to 450°F for the valve, and 300 to 400°F for the pour tube. In practice, the pot temperature was often between 400 and 600°F before Na flow could be started. The reasons for the high temperature requirement are not known with certainty. The most likely cause is accumulation of Na oxide in some part of the flow path, particularly around the filter in the pot.

During a test of the liquid apparatus, Na was poured into a visible open container inside the evacuated retort. The liquid surface retained a bright sheen for 20 min after pouring, indicating the absence of oxygen and moisture inside the vessel.

Cleaning and valve maintenance were the chief operating problems encountered with the liquid handling apparatus. The entire system was cleaned, after each experimental use, by soaking and flushing with butyl alcohol. This proved to be a lengthy process, requiring about 72 hr of soaking time. Otherwise, the cleaning method was satisfactory.

The stainless poppet and seat in the valve became scored so badly that, after the third pot full of Na was poured, Na flow could not be stopped. The working parts were refinished, and satisfactory operation was obtained.

It was necessary to find a method of controlling Na level in the finished fuel rod. Because of the variation in annulus volume (discussed in Section III-B-1), putting a measured volume of Na into each rod did not solve the problem. The possible methods for level control are:

- a) Overfilling, and removing the excess Na after bonding.
- b) Underfilling and adding Na after bonding.
- c) Measuring the level during bonding and filling to the proper level, allowing an excess to compensate for the contraction caused by cooling.

Overfilling and removing the excess was chosen as the most promising method. An excess of molten Na above the fuel is desirable to avoid shrinkage in the annulus. Adding Na after bonding would require reheating to melt the additional metal and would lengthen the bonding cycle.

Figure 10 illustrates one method of removing the excess sodium. An 18-in. long sleeve was inserted into the top end of the cladding. This sleeve extended down to the uppermost fuel slug, and remained in this position through Na pouring and heating. When the bonded rod cooled to between 150 and 200°F, the sleeve was withdrawn from the cladding, taking the excess Na with it.

When bench tested in air, the sleeve method of removing excess Na worked satisfactorily. Despite this, in many of the experimentally bonded rods done in the retort, the sleeve could not be removed after cooling to 150 to 200°F.

Figure 10. Sleeve in Fuel Rod
Gas Space for Removing
Excess Na

Many of the sleeve trials were attempted in rods filled to the top with Na. Destructive examination showed that the high Na level promoted Na bonding between the sleeve and the cladding. The upper 6 in. of the cladding cools rapidly, and the shear strength of the cold Na evidently prevented sleeve removal. When Na level was held within 4 to 6 in. above the upper fuel slug, excess Na was successfully removed from the fuel rod inside the retort.

A method for detecting Na level in the cladding during Na pouring was necessary, for two reasons:

- a) The Na valve could not be closed instantaneously. Some warning of rising level was necessary, to avoid over-filling.
- b) The Na level had to be high enough to avoid shrinkage in the annulus and low enough to allow removal of the sleeve.

An inductive indicating instrument was used to determine NaK level in SRE Core II fuel rods. The SRE design was adapted to the elevated temperature requirements for Na bonding. Figure 11 illustrates the construction of this device. The instrument was used during several of the bonding experiments. It functioned well electrically at elevated retort temperatures. However, false level readings were obtained when Na pouring was too rapid. The instrument correctly indicated Na level when the pouring rate was properly controlled (about 3 min to fill one rod).

Fuel slug surfaces, for most of the bonding work, were cleaned by shot blasting. For comparison, pickled slugs were included in two experimentally bonded rods. Fuel slugs which had been pickled with a solution of 48% nitric acid and 2% hydrofluoric acid bonded very poorly. Fuel slugs which had been pickled in a bath of 50 g/l of chromic acid in concentrated sulphuric acid were mixed with shot-blasted fuel, and no significant difference was detected in the bonding

Figure 11. Na Level Instrument for High Temperature (1000°F) Measurement

(The 3-coil sensing instrument is shown in operating position against the fuel rod. It acts as a loosely coupled transformer, with the center coil as a primary winding and the end coils as secondary windings. The circuit is such that voltages in the two outer coils are opposing. The maximum voltage difference occurs at the Na level shown, producing a maximum meter deflection.)

obtained on the materials cleaned by the two methods. Since all fuel slugs will be shot blasted for inspection, regardless of bonding requirements, there appears to be no advantage in adding a pickling operation.

2. Discussion of Results

The work done on liquid handling confirms the advantages of this bonding technique, compared to the extrusion bonding system. It was demonstrated that an adequate volume of sodium could be poured into fuel rods, while insertion of sufficient extruded sodium into the cladding was difficult. It was also demonstrated that the bonding cycle time, using the liquid method, was shorter than that required by extrusion. The liquid method is much more flexible, in that large changes in the Na volume per fuel rod can be accommodated without equipment or technique changes.

It is likely that the operating problems encountered with the liquid Na apparatus can be solved by improvements in both equipment and technique. To avoid the large time expenditure for cleaning, it is possible to maintain an inert atmosphere inside the equipment continuously, filling the system with Na from

Figure 12. Destructive Examination of a Na Bonded Fuel Rod

Figure 13. Na Bonded Fuel Slugs After Removal of Fuel Rod Cladding (Slugs and Na Are in Air)

an auxiliary pot. In this manner, Na in the main pot, filter, and valve would not be exposed to air, and would remain clean during the inactive period between retort loads. Hard facing of the valve seat and poppet with dissimilar high temperature materials, such as two grades of Stellite, is a promising means of extending valve life.

Soundness in the Na bond is not an absolute requirement. The reactor coolant outlet temperature of 1000°F is certainly adequate to complete bonding in the reactor. It is almost certain that, when fuel elements are removed from the reactor and later reloaded into the core, shrinkage will occur in the Na bond. Cooling of the rods during removal from the core is in the opposite direction to that required for good bonding.

A sound ambient temperature bond obtained during fuel rod fabrication will provide absolute assurance that all fuel and cladding surfaces are clean enough to bond and that the Na level is correct.

D. INSPECTION METHODS

1. Destructive Examination

The Na bond in the experimental fuel rods was examined visually, by manually decanning the fuel slugs in air. Figures 12 and 13 show the stripping operation and the bonded fuel after the cladding was removed. Mechanical means of cutting the cladding were investigated, but resulted in deformation of the sodium near the cladding break, so that complete inspection was not possible. No hazardous incidents occurred during the handling of the bonded slugs in air.

It was found that the sodium bond was self sealing, so that air did not reach the sodium until the instant the cladding was peeled off each small increment of area. Due to this sealing action, the sodium was always bright and clean for a few seconds after the cladding was removed, thereby allowing accurate observation of the bond quality. Most of the voids in the bond were also clearly visible for an hour or more after exposure to air, as can be seen in Figure 13.

All fuel rods which were experimentally bonded were destructively examined, except those assembled in the second full-scale fuel element mockup.

2. Nondestructive Testing

The use of a Cyclograph (Figure 14), an eddy current inspection device, was investigated as a nondestructive method for inspection of the Na bond. This

Figure 14. Cyclograph-Eddy Current Nondestructive Test Machine

device was used effectively for inspection of the NaK bond in SRE fuel rods.

To inspect a fuel rod, using this device, the rod is inserted into a coil, which is part of an oscillator circuit. The amplitude of oscillation is a function of hysteresis and eddy current losses in the fuel rod. A chart recorder provides a permanent record of amplitude changes, with the length of the chart paper corresponding to the fuel rod length.

Several rods were inspected with the Cyclograph, before being destructively examined. Direct comparison of the Cyclograph chart with bonded slugs after decanning showed excellent correlation between Na voids and the variations in oscillator amplitude. Voids as small as 1/16 in. on the largest dimensions were detected by the Cyclograph.

Considerable operating experience is required to properly interpret the Cyclograph charts. A linear void of uniform width in the Na, parallel to the rod length, causes a change in the Cyclograph output only at the ends of the void. The Cyclograph is also sensitive to section changes in the fuel slugs and in the cladding. For example, experience is necessary to detect the difference between fuel slug ends and the end of a long linear void in the Na.

IV. FABRICATION OF FULL-SCALE MOCKUPS

Two 19-rod full-scale mockups were built. In the first, dummy steel slugs replaced the fuel, and the NaK bond was simulated with water. The second mockup contained normal U - 10 wt % Mo fuel and a Na bond. The two mockups were similar in design, with the exception of the hardware above the rod cluster.

The two mockups which were built did not have all the features of the final fuel element design for Core I. The design has been modified to improve nuclear and structural characteristics. Fabrication of a third mockup, to include all modifications, is planned and will be reported separately.

A. FABRICATION PROCEDURE

The following is a description of the fabrication of the second mockup, which is representative of both mockups. Figure 15 illustrates the fuel element design applicable to the second mockup.

1. Component Fabrication

Table VIII lists the method of fabrication and the materials used for each component. The fabrication of fuel rods, including Na bonding by the extrusion method, was described in Section III-B.

2. Subassembly - Fuel Rod Cluster

Figure 16 shows the fuel rod cluster during assembly operations. The sequence of cluster assembly was as follows:

- a) The three 16-ft long spacer connecting wires were threaded through 15 fuel rod spacers. Ferrules were Heliarc welded to the wires on both sides of each spacer.
- b) The cage formed by spacers and wires was lashed into a handling cradle. The cradle and cage were lifted to a vertical position and lashed in place.
- c) The 19 fuel rods were lifted into a vertical position, inside a heavy-wall supporting tube. The fuel rods were lowered, by a hoist, one at a time, into the cage through the spacers.

Figure 15. U 10 wt % Mo for Fuel Element Assembly for Hallam Nuclear Power Facility

TABLE VIII

MOCKUP COMPONENT FABRICATION

Part Name	Material		Fabrication Method	
	Design	Mockup	Design	Mockup
Fuel Slug	U - 10 wt % Mo (approx. 3% enriched)	U - 10 wt % Mo (normal)	Not Included	Vacuum Casting
Fuel-to-Cladding Bond	Sodium	Sodium	Not Included	Sodium Extruded and Heated in Helium Atmosphere
Fuel Rod Cladding	Type 304 Stainless Steel	Type 304 Stain- less Steel	Welded and Drawn	Welded and Drawn
Fuel Rod End Plugs	Type 304 Stainless Steel	Type 304 Stain- less Steel	Machined	Machined
Fuel Rod Hangers	Type 304 Stainless Steel	Type 304 Stain- less Steel	Investment Cast and Finish Machined	Machined from Solid Bar
Fuel Rod Spacers	Type 304 Stainless Steel	Type 304 Stain- less Steel	Die Formed and Spot Welded Strip	Die Formed and Spot Welded Strip
Fuel Rod Spacer Connecting Wires	Type 304 Stainless Steel	Type 304 Stain- less Steel	Drawn Wire	Drawn Wire
Process Tube	Zircaloy 2	Type 304 Stain- less Steel	Rolled and Welded	Rolled and Welded
Adapter (Upper Hardware)	Type 304 Stainless Steel	Type 304 Stain- less Steel	Machined from Tubing	Machined from Tubing
Locking Rings (Upper Hardware)	Type 304 Stainless Steel	Type 304 Stain- less Steel	Machined from Tubing	Machined from Tubing
Hanger Pins (Upper Hardware)	Type 304 Stainless Steel	Type 304 Stain- less Steel	Machined from Bar Stock	Machined from Bar Stock
Lower Guide (Bottom Hardware)	Type 304 Stainless Steel	Type 304 Stain- less Steel	Sand or Centrifugal Cast and Finish Machined	Machined from Tubing
Lower Guide Pins	Zircaloy 2	Type 304 Stain- less Steel	Machined from Bar Stock	Machined from Bar Stock
Fuel Rod Springs	Type 18-8 Stainless Steel Spring Wire ASTM-A313-55	Type 304 Stain- less Steel	Wound from Square Wire and OD Finish Ground	Wound from Square Wire and OD Finish Ground
Fuel Rod Washers and Followers	Type 304 Stainless Steel	Type 304 Stain- less Steel	Machined from Plate and Bar	Machined from Plate and Bar

Figure 16. Fuel Rod Cluster Assembly

- d) The three segments of the upper hanger were fitted, over the fuel rod upper end caps, and Heliarc tack welded together on their outside surfaces.
- e) The connecting sleeve was placed in its final position around the upper hanger. The upper fuel rod spacer, previously assembled loosely over the fuel rod upper ends, was inserted into the bottom of the connecting sleeve and fastened by tack welding a retaining ring to the sleeve.
- f) The pin locking ring was placed inside the sleeve on top of the hanger. The orifice tube was lowered into the sleeve with a hoist. The orifice was turned, to screw it into the sleeve.
- g) The cluster, with upper hardware assembled, was lifted free of the cradle by the hoist. The lower hanger segments were fitted and welded to the bottom of the fuel rods, in the same manner as the upper hanger was fastened to the top end.

- h) The spacer connecting wires were fastened to upper and lower hangers by Heliarc welding ferrules to the wires.

3. Subassembly — Process Tube and Lower Guide

- a) The lower guide was inserted into the lower end of the process tube.
- b) Eight radial holes were line drilled, through both the process tube and the lower guide.
- c) Pins were inserted into the eight holes and Heliarc tack welded at the outside diameter of the process tube, to fasten the lower guide to the tube.

4. Final Assembly — Rod Cluster into Process Tube

- a) The process tube was lashed in a vertical position.
- b) The cluster was lowered into the process tube by the hoist.
- c) Three special pins were inserted into mating holes in the connecting sleeve and the process tube upper end. The orifice was screwed down solidly, to lock the three pins in place.

B. SPECIAL FABRICATION AND HANDLING TECHNIQUES

Most of the fuel element components were machined, or otherwise formed, in a routine manner. The operations which required special attention are described in the following sections.

1. Fuel Rod Spacers

Figure 17 shows a fixture used for forming the strips and spot welding them together. All the pins in the fixture are removable, to allow progressive bending around a circle of strip material. To obtain accessibility for welding, a set of hand-operated pincer-shaped electrodes were attached to a standard spot welder. Small hand-operated dies were used to form the peripheral dimples and the radial ribs.

Spacer dimensional tolerances were considered important, to accurately locate the fuel rods, and to avoid possible damage to rods due to improper fits. Three randomly chosen mockup spacers were dimensionally inspected, at every fuel rod contact point, before cluster assembly. The outside diameter over the dimples was also measured.

Figure 17. Tooling for Fuel Rod Spacer Fabrication

The results were as follows:

Center-to-center location error

average	--	0.005 in.
maximum	--	0.012 in.

Diametral clearance between rod and spacer (rattle)

average	--	0.003 in.
maximum	--	0.0065 in.

Range of variation

outside diameter over dimples -- ± 0.009 in.

It was noted, during cluster assembly, that end closure welds, as much as 0.020 in. larger in diameter than the nominal fuel rod size, caused no visible damage to either the spacers or the rods when the welds were forced through the spacers. End closure welds are not normally 0.020 in. larger than the cladding, but difficulties with leak tightness in the welds, due to the Na bonding technique, caused thick weld beads on some of the mockup rods.

2. Cluster Assembly and Handling

As described in Section IV-A-2, a cradle was used to support the cluster; and a heavy-wall tube, capped on one end, was used to handle individual fuel rods.

It was found that a fuel rod held in the horizontal position would be permanently deformed, by bending, if supported at less than four points along the 15-ft length. During inspection following Na bonding, a mockup fuel rod was damaged beyond repair while being handled without external support. The assembled cluster, without the process tube, is almost as flexible as the individual fuel rods.

The major reason for building the special handling devices was that transportation required horizontal handling of either the individual rods or the entire cluster. Otherwise, all handling could be done vertically, by a crane, with less danger of damage. Vertical handling, during assembly of the cluster into the process tube, was used for another reason. If assembly were done horizontally, the weight of the fuel would be supported by the spacers bearing against the inside of the process tube. High frictional forces would be set up, making insertion of the cluster very difficult.

The dimples on the outside diameter of the fuel rod spacers played an important role in the assembly of the rod cluster into the process tube. The spacers used on the first mockup had no dimples. The sharp edges of these spacers jammed against the inside of the process tube, during insertion of the cluster, and several of the spacers were severely deformed.

The second mockup cluster went into the process tube easily. The dimples acted as spherical bearing surfaces which prevented sharp edges from contacting the process tube. The nominal diametral clearance between the spacers and the tube was 0.02 in.

V. COMPONENT TESTING

A. DESTRUCTIVE TESTS OF FUEL ROD END CLOSURES AND CLADDING SUPPORT SPRINGS

High internal pressures are expected at maximum burnups in HNPF Core I fuel rods. Compared to the solid end plugs used in SRE rods, hollow end plugs appeared to offer an advantage, reducing cladding stress concentrations near the end closure welds. Tests were conducted to check strengths and fabrication problems on end closures with hollow plugs.

During SRE wash cell operations, a few irradiated fuel elements have been damaged by rapid pressure buildups in the cell. Analysis of these incidents has shown that the initial pressure rise was probably due to a reaction between water and the coolant Na that was trapped in the fuel element structure; but that a collapse of the cladding above the fuel admitted water to the NaK bond in the fuel rod, thereby causing additional explosive pressure. To prevent similar action in the HNPF wash cell, a spring was designed to fit into the fuel rod gas space, to back up the thin cladding against external pressure. External pressurization of fuel rod specimens with springs was included in the testing program, to determine the effectiveness of this cladding support scheme.

1. Test Procedure

The tests were performed on short fuel rod sections, consisting of hollow end plugs with 0.03-in. wall thickness welded to cladding with a 0.65-in. OD by 0.01-in. wall thickness. Cladding, end plugs, and springs were all fabricated from Type 304 stainless steel. Specimens with solid end plugs, similar to those used in SRE fuel rods, were also included for comparison. The cladding was 6-1/2 in. long, on internally pressurized specimens; and 4-1/2 in. long, on externally pressurized specimens.

End plugs were welded into both ends of the cladding. On some of the specimens, an axial hole was drilled through one end plug for internal pressurization. The specimens for external pressurization contained 1 atm of inert gas.

End closure welding was done in an atmosphere of 80% helium and 20% argon, inside a dry box. The fuel rod was rotated by a drive motor, during arc welding with a stationary thoriated tungsten electrode.

For the destructive testing, internal pressure was applied by pumping argon into each specimen, with room air on the outside. External pressure was applied by pumping argon into a pressure vessel containing the specimen. All the elevated temperature specimens were held at 1000°F for 15 min before pressure was applied. The externally pressurized specimens were removed from the vessel at several intermediate pressures before failure in order to observe the deformation.

2. Test Results

Table IX shows the complete test data. Typical tested specimens from each group are shown in Figure 18.

It will be noted that there was no significant difference between the failure pressures of the hollow end plug specimens and those of the solid end plug specimens, either at ambient or elevated temperature. Also, there was little difference between failure pressures of end plugs that were force fitted into the cladding and those that were fitted as closely as possible.

Most of the failures occurred in the cladding on the internally pressurized specimens. On some of the ambient temperature specimens, the cladding was torn over the entire length of the specimen, including areas near the end closure weld (see Figure 18). It is possible that failure started near the weld, on these specimens. However, failure pressures were not significantly lower, when cladding was ruptured near the weld, than when failure was away from the weld.

The externally pressurized specimens with the support springs inside showed cladding deformation at low pressures, but rupture did not occur until extremely high pressures were reached. The deformation, as seen in Figure 18, was severe at the high external pressures. However, three of the specimens survived the maximum pressure which the test equipment was capable of producing (10,000 psi).

B. STATIC LOAD TEST OF FUEL ROD SPACERS

Since the loads imposed on the fuel rod spacers during reactor operation are relatively low, an attempt was made to use spacers formed from very thin, 0.010-in. thick, strip material to improve neutron economy. An independent requirement is that spacers must withstand handling, during fuel element fabrication and reactor core loading. To roughly evaluate the ability of the spacers

TABLE IX

DESTRUCTIVE TEST DATA FOR FUEL ROD CLADDING AND END CLOSURES

Description	Test Conditions	Specimen No.	Pressure When Yielding Started in Cladding (psi)	Pressure at Rupture (psi)	Comments
Hollow end plugs, empty cladding	Internal pressure, ambient temperature	4-1	Not Recorded	2600	All failures in cladding
		4-2		2600	
		4-3		2500	
		4-4		2400	
		4-5		2500	
		4-6		2400	
Hollow end plugs, empty cladding	Internal pressure, 1000°F, short time test	X-1	Not Recorded	1800	All failures in cladding
		X		1600	
		4-7		1700	
		4-8		1700	
Solid end plugs fitted to cladding within 0.001 in. empty cladding	Internal pressure, ambient temperature	1-1	Not Recorded	2600	All failures in cladding
		1-2		2500	
		1-3		2400	
		1-4		2200	
		1-5		2400	
Solid end plugs with 0.006 in. interference fit in cladding, empty cladding	Internal pressure, ambient temperature	2-1	Not Recorded	2400	Failures in Cladding
		2-2		2500	
		2-3		2200	Location of initial failure undetermined
		2-4			Failures in cladding
		2-5		2400	
Solid end plugs, empty cladding	Internal pressure, 1000°F, short time test	3-1	Not Recorded	1900	All failures in cladding
		3-2		1500	
		3-3		1600	
		3-4		1800	
Hollow end plugs, springs inside cladding	External pressure, ambient temperature	5-1	600	6500	One end plug collapsed and sheared cladding near weld
		5-2	600	No rupture at 10,000 psi	Severe deformation. One end plug partially collapsed
		5-3	Not recorded	10,000	Severe deformation in both cladding and end plugs. Mode of failure same as 5-1.
Hollow end plugs, springs inside cladding	External pressure, 1000°F, short time test	5-4	200	No rupture at 10,000 psi	Severe deformation in all parts except spring. Both end plugs collapsed
		5-5	Not Recorded. Progress of deformation at higher pressures same as 5-4	8000	Severe deformation, same as 5-4. Failure in cladding at top of a single longitudinal fin
		5-6	Not Recorded. Progress of deformation same as 5-4	No rupture at 10,000 psi	Deformation same as 5-4

Specimen size - 0.650 in. OD x 0.010 in. wall cladding, 6½ in. long on internally pressurized specimens, 4½ in. long on externally pressurized specimens. The hollow end plugs had 0.030 in. thick wall.

Material - End plugs, cladding, and springs were all Type 304 stainless steel.

Figure 18. Cladding and End Closure Test Specimens

Figure 19. Static Loading of Fuel Rod Spacers with Horizontal Rod
(The dimensions of dummy steel rods were such that they equalled the mass of fuel rods loaded with U-10 wt % Mo over the distance between spacers.)

to sustain loads during handling, spacers formed from two different thicknesses of strip material were loaded statically with dummy fuel rods in a horizontal position. The dummy steel rods were of such a diameter and length that the load they imposed on the spacers was equal to the weight of fuel rods containing U - 10 wt % Mo.

The results are pictured in Figure 19. The spacer made from 0.010 in. thick material was severely deformed. The spacer made from 0.016 in. thick material showed no plastic deformation under static loading.

It will be noted that the spacers pictured in Figure 19 differ somewhat in configuration, as well as in material thickness. The 0.010 in. spacer design was largely rectilinear, with many straight line members. The 0.016 in. spacer design was largely curvilinear, with several corrugated members. A spacer (not illustrated) with the rectilinear design was also fabricated from 0.016 in. thick material, and was compared to the 0.016 in. spacer in Figure 19. The load carrying capacity of the two 0.016 in. spacers with different configurations was almost identical. Thus, the geometry of the design was eliminated as a variable in the comparison of spacers with different material thicknesses.

C. THERMOCOUPLE FLEXURE TESTING

The sodium coolant outlet temperature will be monitored, in each fuel element, by an iron-constantan thermocouple having its hot junction located in the variable orifice plug above the fuel rod cluster. The plug will be moved vertically to adjust the orifice opening during reactor operation. The thermocouple leads between the orifice and the shield plug must accomodate the plug motion.

One design possibility utilizes a spiral wound section in the thermocouple leads which will expand or compress like a coil spring when the orifice plug is moved. Thermocouple flexure tests were run to determine the effects of the spring action on thermocouple performance. The number of flexure cycles anticipated during the life of a fuel element in the reactor is approximately 100.

1. Test Procedure

The test apparatus is shown in Figure 20. For each type of thermocouple tested, a coil which was made of the thermocouple leads, with insulation and sheath tubing, was heated in air and flexed repeatedly by compressing and expanding the coil.

Figure 20. Test Apparatus for Thermocouple Flexure

The thermocouple hot junction was in the hot zone of the furnace, and the thermocouple was connected to a temperature recorder throughout the flexure testing.

A description of the thermocouples tested and the test conditions is given in Tables X and XI.

2. Test Results

The following thermocouple characteristics remained unchanged throughout all tests:

- a) Emf output
- b) Resistance of the thermocouple wires
- c) Resistance between thermocouple wires and the sheath

Visual examination of the sheaths after testing revealed no cracks.

TABLE X

THERMOCOUPLE DESCRIPTION FOR THERMOCOUPLE FLEXURE TESTS

Specimen No.	Wire		Insulation Type	Sheath		
	Type	OD (in.)		Type	OD (in.)	Thickness (in.)
1	Chromel-Alumel	0.020	Zirconium Oxide	304 SS	0.125	0.015
2	Chromel-Alumel	0.020	Zirconium Oxide	304 SS	0.125	0.015
3	Chromel-Alumel	0.020	MgO Hard Pack	304 SS	0.125	0.015
4	Chromel-Alumel	0.020	MgO Hard Pack	304 SS	0.125	0.015
5	Iron-Constantan	0.024	MgO Regular Pack	304 SS	0.125	0.017

TABLE XI

TEST CONDITIONS FOR THERMOCOUPLE FLEXURE TESTS

Specimen	Stroke (in.)	Temperature (°F)	Approx. Frequency (cph)	Time (hr)	Cycles
1	Extend 2 Compress 2	1000	600	8	5,000
2	Extend 2 Compress 2	225	2400	2	4,800
		225-1000	1100	2	2,200
		1000	1500	4	6,200
3	Extend 2 Compress 2	1000	1	200	200
4	Compress 4	1000	3000	14	45,000
		70	6000	8	48,000
5	Compress 4	1000	3000	16	50,000
		70	3000	16	50,000

VI. CONCLUSIONS AND RECOMMENDATIONS

A. FUEL SLUG FABRICATION

Casting was demonstrated to be an economical method for fabricating U - 10 wt % Mo fuel slugs of adequate quality. The quality limits which were maintained during the development program were:

Density (g/cc)	17.00 to 17.25
Mo Content (%)	10.00 $\pm$ 0.50
C Content (ppm)	800 maximum
Diameter (in.)	0.590 $\pm$ 0.005
Straightness	0.020 in. max. bow in 12 in. (after homogenization)
Surface Finish (rms)	230 maximum

Since the heat treatment has not been selected for Core I fuel, methods were investigated for both homogenization and transformation of cast U - 10 wt % Mo slugs.

The recommended heat treatment for gamma homogenization of cast U - 10 wt % Mo fuel is 1000°C for 8 hr in vacuum and cooling in vacuum. The optimum heat treatment for 100% transformation from a homogenized gamma structure to alpha plus gamma prime is 475°C for 250 hr in vacuum, cooling in vacuum. Partial transformations can best be obtained at 475°C for shorter times.

B. Na BONDING OF FUEL RODS

The experimental bonding showed that:

- 1) HNPF fuel rods can be satisfactorily bonded, utilizing liquid handling of Na for rod filling in vacuum.
- 2) Either shot blasting or pickling is satisfactory for cleaning fuel slug surfaces prior to bonding. Shot blasting is more economical.
- 3) Eddy current inspection of the bond is a satisfactory nondestructive test method, but depends largely on the skill of the inspector.

Further work is required for:

- 1) Establishing reproducibility and scrap rates for the liquid filling technique of bonding.

- 2) Improving operation of the liquid Na apparatus. Hard facing of the valve poppet and seat with Stellite is recommended for extending valve life. The practice of keeping the main system under inert atmosphere, when not in operation, and Na filling from an auxiliary pot deserves trial as a means of reducing cleaning time.
- 3) Analyzing Na from experimental runs for O_2 content to insure that the stainless cladding is not corroded. O_2 content can be reduced, if necessary, by adding a cold trap to the Na pot.

C. FULL-SCALE MOCKUPS

Fabrication feasibility was demonstrated for the fuel element design shown in Figure 15.

The most difficult structural component to fabricate was the fuel rod spacer, due to the requirement of close tolerances in thin material. The best accuracy for fuel rod center location which can be obtained, on a practical basis, is ± 0.012 in. It is recommended that manufacturing tolerances on the spacers be no closer than ± 0.010 in., on overall dimensions, and ± 0.005 in., on dimensions within any one of the six segments.

Final assembly of the fuel rods into a cluster and of the cluster into the process tube must be done with these components in the vertical position. It is recommended that horizontal handling of either the cluster or individual fuel rods (e.g., loading in a shipping container) be done with a cradle or containing tube which provides full length support.

D. COMPONENT TESTS

1. Fuel Rod Cladding End Closures

The destructive tests performed on fuel rods indicated the following:

- a) End closures made by welding hollow end plugs with 0.03 in. wall thickness to cladding with 0.01 in. wall thickness will withstand as much internal pressure as the cladding. The material in the cladding and end plugs tested was Type 304 stainless steel.
- b) A square wire spring in the fuel rod gas space is a satisfactory device for preventing the cladding from collapsing and rupturing due to high external pressures.

c) During assembly of end plugs and cladding before welding, interference fits, varying from zero to 0.007 in., have no effect on the strength of the end closure. Consequently, by using tapered end plugs, it is possible to allow ± 0.003 in. tolerance on the cladding diameter without jeopardizing end closure quality. Selective fitting of end plugs to cladding can also be avoided in this manner.

2. Thermocouple Flexure

The tests performed showed that there is little danger of thermocouple inaccuracy or failure, due to the flexing action above the variable orifice plug in the HNPF fuel element hanger.

3. Fuel Rod Spacers

A minimum strength requirement for practical handling of assembled fuel elements is that the spacer must statically support a horizontal cluster in the process tube. The tests performed indicated that the spacer strips must be at least 0.016 in. thick, to meet this criteria. This conclusion is only valid for 1 ft longitudinal distances between spacers and for 3/8 in. long spacer segments.

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