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FABRICATION OF EBR-II, CORE I FUEL ELEMENTS

by

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R. H. Olp, and A. B. Shuck

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FABRICATION OF EBR-II, CORE I FUEL ELEMENTS

by

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SUMMARY

A total of 10,781 fully inspected fuel rods were manufactured for EBR-II Core I by processes adaptable to remote operation. They were assembled from carefully measured fuel pins and jacket preassemblies. A precise volume of sodium was incorporated in each fuel rod. They were closed by restrainer plugs which were capacitor-discharge welded into the top of the jackets. The welds were leak detected and the voids were eliminated from the sodium bond by a vibratory heat treatment.

Each fuel rod was carefully inspected. Bond voids were detected by means of an eddy-current technique. The height of the sodium level was verified by the use of X rays. Length, straightness, and tip dimensions were gauged. All rods not meeting the specifications (a total of 3,881) were dejacketed and reloaded. Improper sodium level was the cause of nearly one-half of the rejections.

The fuel rods were assembled into 55 (91-rod) fuel elements, 42 (91-rod) blanket-region fuel elements, 14 (61-rod) control elements and three each of (61-rod) safety and poisoned safety elements. An additional 26 (91-rod) "simulated fuel elements" were made with normal uranium-fissium alloy "simulated fuel pins." The simulated rods and elements were made for manufacturing and reactor systems testing. They will also be used for preliminary testing of the equipment for remote fuel recycle.

Element assembly began with the placing of a lower preassembly in a remotely operated jig. The fuel section was assembled on an attachment grid atop the preassembly. It was heated to melt the sodium and to simulate fuel-recycle conditions. A hexagonal-tube preassembly was forced over the fuel and welded to the lower preassembly. The finished elements were gauged for all critical dimensions and straightness. The welds were proof tension tested at 3,000 lb. Straightness was the principal source of rework. More than $\frac{2}{3}$ of the assembled fuel elements required straightening.

*Reactor Engineering Personnel. The manufacture of EBR-II Core I elements was a joint effort by Metallurgy and Reactor Engineering personnel.

INTRODUCTION

The EBR-II core components have been variously named by different groups. For purposes of this report, a "fuel pin" is a 0.144-in.-diameter by 14.22-in.-long cylinder of enriched uranium-5 w/o fissium alloy. A "simulated fuel pin" is similar in all respects but enrichment. The manufacture of pins is described in ANL-6274.⁽¹⁾ A "rod" is a jacketed and sodium-bonded pin. The components and dimensions of a typical fuel rod are shown in Figure 1. For consistency, the jacketed and bonded blanket material is termed "blanket rod."

106-6618

Figure 1. EBR-II Fuel Rod

The term "element" is applied to the loading unit of the reactor. A typical "fuel element," containing 91 fuel rods, is shown in Figure 2. "Blanket-region fuel elements" are similar to fuel elements but have lower adapters that fit inner blanket region sockets in the reactor support grid. A "control element" is a 61-rod moveable assembly which couples to the reactor control mechanism. A "safety element" is a 61-rod moveable assembly that connects to the reactor safety mechanism.

106-5982

Figure 2. EBR-II Fuel Element

The purposes of Program 7.10.8 were as follows:

- (1) to assemble and test EBR-II Core I fuel rods;
- (2) to assemble and test EBR-II Core I fuel elements;
- (3) to evaluate the manufacturing techniques proposed for the EBR-II fuel cycle in a sustained operation; and
- (4) to test proposed remotely operable equipment under production conditions.

The work was performed in a special facility described in ANL-6092.(2)

FUEL RODS

All fuel alloy was contained in fuel rods (see Figure 1). Right-cylindrical fuel pins were contained in, and sodium bonded to, stainless steel jackets. Each jacket consisted of a length of AISI Type 304L stainless steel tubing to which was welded a cast, stainless steel tip. The tip was contoured to fit the T-bar grid atop the lower element section. A

single wire was spiraled up the outside of the rod and welded at each end. It provided uniform spacing between the rods of an element and also improved the coolant flow pattern. A restrainer plug was welded in the top of the jacket after the fuel pin and sodium were loaded.

Fuel pin and jacket were thermally bonded. A void space was provided in the top of each rod for the collection of fission gases. The restrainer prevented the fuel pin from rising above the sodium level during operation. A minimum of 10,047 acceptable fuel rods was needed for the fuel, control, and safety elements. In addition, 2,366 simulated fuel rods were required for the 26 simulated fuel elements.

CORE ELEMENTS

The core section of a fuel element, shown in Figure 2, was enclosed in a hexagonal tube fitted with a top end fixture and lower adaptor. Ninety-one fuel rods, in hexagonal array, made up the core section. The fuel rods fitted to a T-bar grid atop the lower blanket section. Each blanket section contained 18 blanket rods in hexagonal array. A blanket rod contained depleted uranium enclosed in, and sodium bonded to, a stainless steel jacket tube.

Control and safety elements contained only 61 fuel rods. They were smaller in diameter and operated within a hexagonal tube of the size used for fuel elements. The control and safety elements did not contain blanket sections.

MANUFACTURING OPERATIONS

The operations for element manufacture are outlined in Figure 3. They can be divided into two processes: (1) fuel-rod assembly and (2) element construction. Those operations within the dashed enclosure were performed in an argon-atmosphere glovebox.

The components delivered to the process were: (1) enriched uranium-5 w/o fissium alloy fuel pins, (2) fuel jacket preassemblies, (3) sodium extrusion billets, (4) restrainer plugs, and (5) upper and lower preassemblies. The length, average diameter, and weight of each fuel pin were supplied to the nearest 0.001 in., 0.0001 in., and 0.1 gm, respectively. Fuel-pin structure, a metastable structure containing retained gamma phase, was usually that produced by casting. The preparation of preassembled fuel jackets and restrainer plugs is described in ANL-6518.(3)

106-6732

Figure 3. Operations Comprising Core I Element Manufacture

As delivered, a jacket consisted of a fuel tube with tip element and spacer wire attached, ready to accept a fuel pin and sodium. The preparation of upper and lower preassemblies is described in ANL-6518⁽³⁾ and ANL-6418.⁽⁴⁾ Typical fuel-element preassemblies are shown in Figure 4. Hexagonal tube preassemblies, each containing an upper blanket preassembly and lower blanket preassemblies, were delivered to be processed. Comparable preassemblies were used in the assembly of control and safety elements.

106-6728

Figure 4. Fuel-element Preassemblies

NUCLEAR HAZARD CONTROL

Manufacturing procedures were carefully reviewed for nuclear safety by the ANL Criticality Hazard Control Committee. The work area was made an exclusion area, and manufacturing conditions were closely supervised. The area was divided into zones with brightly colored tape applied to the floor. The amount of fuel alloy permitted in each zone was limited on the following basis:

- (1) The amount of fuel alloy in each zone must be less than a pre-approved mass.
- (2) The total amount of fuel alloy in adjacent zones must be less than a preapproved mass when brought together at the zone boundaries.

The amount of fuel alloy allowed in a zone and the amount actually present were posted near the zone at all times.

To insure close control of movement of fuel alloy, all responsibility for interzone transfer was rotated between attending engineers who made all transfers and kept a continuously current record of the amount and distribution of fuel alloy within the work area.

Zonal limits were fixed assuming high reflection but low moderation. All liquids were kept out of the work area except when in containers of safe geometry. Floor drains were sealed and overhead water lines disconnected. All containers were equipped either with seals, so that liquids

could not enter, or with drains, so that liquids could not be retained. Fuel alloy was never placed on the floor. In addition to these precautions, all personnel employed in the area were indoctrinated in the approved procedure.

FUEL-ROD ASSEMBLY

The preassembled jacket was loaded with sodium and prepared to accept a fuel pin. The pin was loaded and settled in the sodium, a restrainer plug was inserted and settled, and the closure weld was made. The finished rod was inspected and, if acceptable, set aside for assembly into fuel, control, or safety elements. Element construction included the fitting together of fuel rods and preassembled sections to make elements that were subsequently welded and inspected.

The nominal dimensions and tolerances for the fuel rods and their components are given in Figure 1. The sodium level was specified at 0.65 ± 0.1 in. above the fuel pin. This tight specification was needed to assure submergence of the pin and also provision of sufficient space above the sodium for the accumulation of gaseous fission products. There were also two qualitative specifications: (1) the closure weld must not pass sodium or fission products during reactor operation, and (2) the jacket and the fuel pin must be wetted by the sodium.

Fuel rods were assembled and transferred in groups of 50. A batch consisted of two such groups in which the rods were numbered consecutively from 1 to 100. The identity of the individual rods was maintained by transporting a group in a single basket having individual, numbered positions.

Manufacturing operations performed with exposed fuel alloy or sodium were carried out in a glovebox equipped with an argon atmosphere. Materials were transferred into and out of the glovebox through vacuum locks. An argon-purifying system was used to remove oxygen and moisture. In practice it was found that some moisture in the atmosphere was desirable since it made the sodium easier to handle. Most efficient operation was achieved when the glovebox atmosphere contained 30 to 50 ppm water vapor. Oxygen was maintained at less than 0.1 percent.

Gauging and Classification of Fuel-jacket Preassemblies

It was necessary to know the average bore diameter of each jacket in order to determine the amount of sodium put in each fuel rod. The average bore diameter was measured by means of a wand-type pneumatic comparator gauge. Five pairs of diameter readings were taken at equidistant intervals along the length of the jacket tube. Each pair consisted

of measurements made 90° apart. The 10 readings were averaged to obtain a representative diameter for the jacket. The accuracy of this technique was verified by weighing 50 jackets empty and filled with water. The volumes so obtained were converted to diameter and compared with measured values. The difference averaged 0.0001 in. with a standard deviation of less than 0.0001 in.

Fuel jackets were accepted if (1) their average inside diameter was between 0.1555 and 0.1565 in., and (2) at least 9 of the 10 individual measurements were within this range. Acceptable jackets were separated into 10 classes according to their average diameter, with the range of each class being 0.0001 in.

Preparation and Loading of Sodium

Sodium was loaded in the form of $\frac{1}{8}$ -in.-diameter extruded wires approximately $4\frac{1}{4}$ in. long. The equipment used in the making and handling of the sodium wires is shown in Figure 5. Sodium was cast into extrusion cylinders. Each cylinder consisted of an 11-in.-long section of 1-in.-diameter pipe capped at both ends. One end cap contained the extrusion

106-6449

Figure 5. Sodium Loading Equipment

die and the other was removed when the cylinder was in use. The extruder incorporated a gear-driven, threaded ram powered by a $\frac{1}{8}$ -hp electric motor. Ram travel was 0.3 in./min. Extrusions were supported in a semicircular trough. The extruded sections were cut to length by an adjustable, double-bladed cutter and then weighed. Each length was straightened by rolling it between two flat, Lucite plates. It was placed in the appropriate jacket using a special tweezers. It was not feasible to straighten the sodium wires before final cutting. If cutting was done after straightening, weight was unpredictable.

The sodium wires were cut for use with a predetermined class of jacket; however, it was found advantageous to have jackets of several classes available at the loading station. If a wire was too light to be used with the jacket for which it was cut, it was placed in a smaller jacket. The chief causes of underweight wires were entrapped gas and sticking dies.

The amount of sodium put in a jacket was dependent on three quantities: (1) the class of the jacket, (2) the average diameter of the batch of fuel pins to be loaded, and (3) the expected shrinkage of the fuel pins in subsequent manufacturing operations. The first two quantities were accurately known; however, the third was not constant and depended on the amount of retained gamma structure. Initially, the sodium loads were calculated assuming a uniform diameter decrease of 0.0003 in. during bonding. When production data became available, loads were predicted almost completely from quality control data. The weight of sodium loaded was usually between 0.8 and 0.9 gm.

Sodium Meltdown

The loaded jackets were placed in a leak-tight, resistance-heated furnace, 3 in. in ID x 19 in. deep, which was sealed through the glovebox bottom. The furnace pressure was reduced using a roughing pump, and the jackets were heated slowly to 150°C. The vacuum pump was isolated, the furnace opened to the glovebox atmosphere, and the temperature increased to about 450°C. The power was then turned off, and the jackets were allowed to cool to room temperature.

The purpose of the meltdown operation was to form a dense, homogeneous, gas-free sodium deposit at the bottom of the jacket. The sodium was melted carefully to insure that none was forced up the jacket walls by entrapped gases, for sodium on the jacket lip interfered with closure welding. When the sodium was completely melted, the furnace was opened to the glovebox and the temperature increased to promote wetting of the lower jacket wall.

When cool, the sodium-filled jackets were ready to accept a fuel pin.

Fuel-pin Loading and Settling

Fuel pins were placed in their jackets by hand, and the assemblage was given the designation of the fuel pin it contained. As loaded, the pins extended above their jackets. They were settled by melting the sodium in a vibratory furnace. The three main parts of the settling furnace were: (1) a 10-rod capacity basket, (2) a resistance-heating element, and (3) a 60-cps Syntron vibrator. The jackets were heated to 150°C and vibrated until the fuel pins dropped. Restrainer plugs were then inserted, and settling continued until the restrainers dropped into position. Approximately 30 min were required to settle a batch of 50 gravid jackets.

Closure Welding

Fuel-rod closure welds were made with a stored-energy, arc-welding machine developed by Stone and Noland⁽⁵⁾ at ANL. It was designed specifically to achieve fusion of the thin-walled jacket tubes without sagging. This completely automated welder was programmed to perform the following operations sequentially: (1) capacitor charging, (2) setting of electrode gap, (3) gas purging, (4) electrode heating, (5) capacitor discharging, (6) gas purging, and (7) indexing. Power was supplied by a 3-kw motor-generator set.

The welding station is shown in Figure 6. The welding basket was indexed by use of a gas motor coupled to a Geneva gear drive. Thirteen positions were available, ten for welding and three for advancing and retracting the welding gun into the welding or unloading positions. A thoriated-tungsten electrode and a helium gas blanket were used.

106-4317

Figure 6. Welding Station

The restrainer top was a solid plug, $\frac{1}{4}$ in. long, with a projecting tip. The tip served as an aid in positioning the arc and in maintaining nearly constant arc length during welding (see Figure 7). The reduced section of the restrainer plug served to insulate that portion of the plug from the gas-cooled jacket wall and produce a desirable thermal gradient. Normally, fusion of the jacket wall was confined to the top 5 to 10 mils.

Macro 34095

Figure 7. Weld Joint

During Core I manufacture, 14,662 fuel rods were welded. Of this number, 1,821 had to be rewelded and 626 were eventually rejected for poor quality of the closure weld. The two main causes of rejects were: (1) the presence of sodium in the weld area, and (2) misalignment between electrode and fuel rod. Sodium, splashed up into the weld area during meltdown or settling, vaporized during welding, and caused a poor and irreparable weld. Misalignment between electrode and rod was usually caused by uneven burning of the electrode or incomplete indexing. In most cases, rejects due to misalignment could be rewelded satisfactorily.

Leak Testing of Closure Welds

Closure welds must be impervious to liquid sodium and fission products. This could be guaranteed only if the welds were leak tight. Two leak detection methods were used, both of which utilized the void space within the fuel rod.

In the first method,⁽⁶⁾ the weld was enclosed in a tightly fitted chamber and a metered amount of gas injected into the chamber. When no leaks were present, a predictable chamber pressure resulted. If a large leak was present, the internal volume of the fuel rod was added to the volume of the chamber and a lower pressure resulted. Smaller leaks were indicated as a pressure decay.

The equipment to perform pressure leak testing is illustrated in Figure 8. It included a pneumatically actuated fuel-rod carrier and a test chamber. The upper end of the carrier was machined for a seal gasket. When the fuel rod was positioned in the carrier, the seal gasket was placed over the upper end just below the weld. The carrier was pivoted to

a vertical position and elevated to insert the weld section of the rod into the chamber. The gasket sealed the fuel rod in the chamber. The test chamber was fitted with a Sheffield "Precisionaire" pressure-sensing element. It sensed the flexure of a diaphragm by means of an orificing jet. Chamber pressure was indicated by a float-type flowmeter that measured air flow between the jet and the diaphragm.

Figure 8
Pressure Leak Detector
System

106-6731

Argon at 620 psig was the pressurizing gas. (Helium would have provided greater sensitivity but would have interfered with adjacent helium leak detection.) Pressure was observed for 2 or 3 min. Recycle time was 5 min. Two detectors were used, allowing 24 fuel rods to be tested per hour.

Pressure leak detection was not proven at this time and was thought to be capable of detecting large leaks only. Therefore, a second method was used to find smaller leaks. The technique involved forcing helium gas into the rod in a pressure chamber and detecting helium bleed-out in a vacuum chamber. This method was excellent for finding small leaks but could not detect large leaks.

In practice, a basket containing 10 fuel rods was placed in a chamber equipped for vacuum and pressure. Chamber pressure was reduced to $50\ \mu$ and then increased to 20 psig by back filling with helium. The chamber was opened and the basket transferred to a second leak-tight chamber. It was evacuated to a pressure of $30\ \mu$ and connected to a conventional helium leak detector for continued evacuation. If helium was detected, one of the rods was a leaker. It was found by elimination, usually in 3 or 4 cycles. Two sets of chambers were used and basket transfers were made by means of a pneumatically actuated cross head. With this detector one man could test 125 rods per day.

Since the sensitivity of the helium bleed-out sampling technique was questioned, a test was made to correlate bleed-out results with more conventional helium leak detection. A group of 210 welded ends were cut from rods tested with the production leak detector at a fixed sensitivity. Of these, 200 passed the bleed-out leak test and 10 did not. The rod ends were divided into 4 groups and submitted to four different treatments before being pressurized with helium and "sniffed" directly using a conventional probe. The treatments were intended to open leaks which might have been sealed by the formation of sodium oxide. "Plugging" was thought to play an important part in leak detection.

The results of the test and the treatments used are given in Table I. Group 1 was given the first treatment and then leak checked. Then Group 2 was added so that both Groups 1 and 2 were submitted to the second treatment and leak tested. This practice was continued so that in the end Group 1 had been submitted to all four treatments whereas Group 4 was submitted to the last treatment only. All treatments should affect the dissolution of sodium oxide. The results of the test were that no new leakers were found. The results of the production bleed-out technique were confirmed by the results of the more conventional helium leak test. The geometry of the production test did not tend to decrease significantly the sensitivity of helium leak detection and the plugging of leaks did not appear to be a problem.

Table I

LEAK DETECTOR PERFORMANCE CHECK DATA

Groups Tested	No. of Welds Tested	Status before Test		Status after Test		Status Change		Treatments
		Nonleaker	Leaker	Nonleaker	Leaker	Nonleaker	Leaker	
1	53	50	3	50	3	0	0	Submerged in boiling water for 8 hr
1	53	50	3	50	3	0	0	Submerged in 10 v/o nitric acid at 66°C for 6 hr
2	53	50	3	50	3	0	0	
1	53	50	3	50	3	0	0	Subjected to 427°C steam for 24 hr.
2	53	50	3	50	3	0	0	
3	54	50	4	50	4	0	0	
1	53	50	3	50	3	0	0	Subjected to 3 mm Hg absolute pressure at 427°C for 8 hr
2	53	50	3	50	3	0	0	
3	54	50	4	50	4	0	0	
4	50	50	0	50	0	0	0	

Bonding and Bond Testing

Bonding was an operation in which heat and mechanical energy were used to produce a void-free sodium volume that wetted both fuel pin

112-703

Figure 9. Typical Fuel-rod Defects

and jacket surfaces. The purpose of bonding was to eliminate (1) voids in the sodium-filled pin-jacket annulus, (2) bubbles under the restrainer, and (3) sodium trapped in the upper restrainer region (see Figure 9). Non-destructive inspections of bond quality and sodium level were performed by means of an eddy-current technique and radiography, respectively.

A vibratory furnace, a 50-rod magazine, and an air blower were the major pieces of bonding equipment (see Figure 10). The furnace had a cylindrical heater assembly made up of concentric upper and lower resistance-heating elements. The heating elements were controlled individually and baffled for more uniform heat distribution. A 60-cycle, resonantly tuned vibrator in the furnace base imparted vertical motion to the rods. Vibrator motion was transmitted through four coupling rods to a $7\frac{3}{4}$ -in.-ID x $12\frac{1}{8}$ -in.-OD ring-shaped platen which struck sockets in the magazine.

Figure 10

Bonding Equipment with External Insulation Removed

111-8095

The bonding magazine was a hollow, cylindrical container open at the bottom. Fifty tubes, spaced equidistantly on a 10-in.-diameter circle, held the fuel rods. Each tube had a loose-fitting socket which extended below the tube and transmitted motion from the vibrating platen directly to the fuel rod. The sockets, which were free to move within the tubes, were made of 18-4-1 high-speed tool steel heat treated to a hardness equivalent to 59 Rockwell C. The sockets were contoured to the fuel rod tip. They had a useable life of 40 to 45 bonding cycles.

The blower promoted a desirable thermal gradient in the cooling sodium after bonding. Room air was forced upward through the magazine tubes.

Fuel rods were placed in the bonding magazine, and the latter was put in the vibratory furnace. The furnace was turned on and "tuned" before the heaters were energized. The fuel rods were heated to approximately 525°C and vibrated for 2 hr. The magazine was then taken from the bonding furnace, placed on the blower, and cooled to room temperature. Approximately $3\frac{1}{2}$ hr were required to bond 50 fuel rods.

Inspection for voids, bubbles, and trapped sodium was by means of a 250-turn, AWG Size 40 wire, eddy-current induction coil connected to a DuMont Cyclograph. When operated at a frequency of 90 kc, this device was able to detect voids smaller than $\frac{1}{16}$ in. in diameter. Voids $\frac{1}{16}$ in. wide by $\frac{3}{32}$ in. long were deemed acceptable. Sensitivity was held constant by means of standards containing voids of known size.

The bonding magazine was transferred from the blower to the machine for bond inspection. Indexing of the machine was automatic, and the fuel rods were raised individually through an inspection coil by a lifting device located below the table supporting the inspection machine. Approximately one hour was required to inspect a group of 50 fuel rods. Acceptable rods were radiographed to determine sodium level. Rejected rods were recycled through bonding.

Those fuel rods having an inappropriate sodium level, as determined radiographically, were destroyed. The fuel pins were stripped, cleaned, and weighed to insure that no damage had been done during manufacturing or stripping. If the weight stripped agreed with the weight as received, the pin was recycled. Damaged pins were either reinspected and recycled or destroyed.

ELEMENT CONSTRUCTION

Element construction consisted of (1) inspection of fuel rods and preassemblies, (2) assembly of fuel bundles, (3) assembly of elements, (4) welding of the hexagonal tubes to the lower preassemblies, and

(5) inspecting the completed elements. The 91-rod elements were assembled remotely while the 61-rod elements were assembled by hand. The development of the remote assembly equipment is discussed in ANL-6272.⁽⁷⁾

The number and type of elements assembled is given in Table II. There were four types of 91-rod elements. The fuel and the simulated fuel were geometrically identical. The other types differed from the fuel chiefly in their lower preassemblies. The assembly technique for all 91-rod elements was similar once the correct lower preassembly was selected. The differences between the three types of 61-rod elements were also in the preassemblies used.

Table II

BREAKDOWN OF ELEMENTS PRODUCED

Type of Element	No. Fuel Rods Contained	Uranium	Quantity Produced
Simulated Fuel	91	Natural	26
Fuel	91	Enriched	55
Blanket-region Fuel	91	Enriched	18
Special Blanket-region Fuel	91	Enriched	24
Control	61	Enriched	14
Boron Control	61	Enriched	3
Safety	61	Enriched	3

Inspection of Element Components

Each element component was inspected. Fuel rods were checked for straightness, damage to the tip of the element, maximum dimensions through welds, concentricity of the closure weld, dents, nicks, and abrasions. Preassemblies were inspected for overall physical dimensions. Particular attention was paid to the T-bars atop the lower preassemblies and to the alignment of parts. Of the 10,151 fuel rods inspected, only 104 were found to be unuseable. All preassemblies were accepted.

Ninety-one-rod Element Assembly

The simulated fuel elements were the first assembled and served as a pilot for the fuel elements. Experience during their assembly was used in finalizing designs for both the fuel element and the assembly machine.

The simulated fuel elements were assembled remotely by means of equipment under development for hot-cell operation. Because of

radioactive heating, it was anticipated that the temperature of the recycled fuel rod would be above the melting temperature of sodium; therefore, the equipment was designed to assemble elements in a vertical position. The assembly machine, shown in Figure 11, was an 8-ft-high structure that supported the assembly equipment at three main levels. A set of guide rings and a cylindrical resistance heater were supported at the upper level. The middle level, shown in Figure 12, supported the rod-loading equipment plus equipment to clamp, heat, and cool the rod bundle. Six pneumatically operated welding guns were mounted on the lower level. The station was operated with a pair of Model-8 Masterslave Manipulators. A programmer at the operator's station indicated the proper loading sequence by means of lights.

Assembly began with the placing of 91 inspected rods in a rack at the assembly station. A lower blanket preassembly, held in a special grapple tool, was lowered into the assembly station. It was positioned at the proper height and clamped in place. A loading plate was moved up to align a set of matching T-bars with those atop the lower blanket preassembly.

A block containing 11 numbered loading guides stood on the loading plate. Each guide connected to a matching T-bar by a guide wire. A rod was taken from the rack and placed in the proper loading cylinder which locked it onto a guide wire. The rod was moved along the wire to its place in the element. A special loading funnel was used with the manipulator to simplify inserting and sliding the rods.

Each loading guide was equipped with electrical contacts which prevented loading in any sequence other than that programmed. The orientation of the rod on the grid was controlled by a "go, no-go" mechanism in the loading cylinders. When a properly oriented rod was placed in the correct loading guide, that cylinder depressed. The rod was locked onto the guide wire, and its position was indicated on the control panel as being loaded.

After each row was assembled, the rods were pushed into position by a manipulator-operated packer bar and held by a blade. When all 91 rods were on the grid, the bundle was squeezed into the proper shape using the two forming clamps above and to the side of the assembly chamber. The hexagonal-tube preassembly was forced down over the rod bundle as the clamps and holders were progressively removed. The preassembly was lowered until the hexagonal tube seated on the shoulder of the lower adaptor.

The hexagonal tube was welded to the lower adaptor by six shielded-arc spot-welding guns. One $\frac{3}{8}$ -in.-diameter weld was made on each face of the tube. Weld quality was controlled by periodically submitting test specimens to a tensile test. All specimens withstood tensile loads in excess of the 3,000 lb specified.

111-8812

Figure 11. Fuel Element Assembly Machine and Gauging Fixture

Figure 12

Rod Bundle Assembly
Equipment

111-8808

Elements were taken from the assembly station and placed in the gauging fixture shown on the right in Figure 11. The element was held in the fixture by its lower adaptor. Dial indicator readings were taken in the center of the tube flats at two levels, at the middle of the hexagonal tube and at the top. The indicators were calibrated to read the distance between the flats of the elements tested and those of a straight element of nominal dimensions. The maximum permissible indicator reading was 0.045 in. Elements not meeting this specification were hand straightened and retested.

To achieve maximum fuel rigidity, ribs were pressed into the hexagonal tube at the fuel section. Two sets of ribs were used. An upper set contacted the fuel bundle above the spacer wires and a center set contacted the spacer wires. Ribs with depth enough to produce the desired rigidity interfered with the rod bundle and caused damage during cold assembly. To prevent this damage, the ribbed section of the hexagonal tube was heated just before assembly. The fuel bundle was also heated to melt the sodium and allow the rods to squeeze together as the ribs passed.

During assembly of the simulated fuel elements, a study was made to determine optimum assembly conditions, i.e. best rib position and depth, best tube and bundle temperatures, and best top-end force. Work was not completed on the simulated fuel elements and had to be carried on through the first 15 fuel elements. The position and depth of ribs found best is illustrated in Figure 13. The top 8 ribs, which were fixed during assembly of the first 5 elements, have a depth of 0.050 in. The number of center ribs was varied from 6 to 11 and their depth from

0.017 to 0.025 in. before the configuration shown in Figure 13 was adopted. Bundle temperature was varied from 105°C to 125°C and tube temperature from 150°C to 482°C. Best results were obtained with a bundle temperature of 110°C and a tube temperature of 400°C.

106-6730

Figure 13. Ribbed Section of Fuel Element Hexagonal Tube Preassembly

No optimum value of top-end force was found. The force required depended not only on conditions in the fuel zone, but also on the clearance between the lower adaptor and the hexagonal tube. Additional force was

often needed to seat the tube on the lower adaptor. The manner of applying the top-end force was found to be important. Initially, the hexagonal-tube preassemblies were lowered over the rod bundles by a crane, and force was applied by weighting the crane grapple. Because the lowering time was not sufficiently short or reproducible, a jacking and guiding mechanism was installed. It lowered the preassembly by means of two motor-driven screws. Limit switches allowed the preassembly to be lowered quickly to where the tube ribs contacted the rod bundle and then slowly as the ribs passed along the bundle. Lowering time was short and reproducible, making for good temperature control of the tube and minimum damage to the fuel rod.

After the simulated fuel elements were completed, the remainder of the 91-rod elements were assembled. Assembly was by type of element, with the station being converted for each type. Conversion consisted of changing the upper guide ring and the lower preassembly-locating rings. All but the special blanket-region fuel elements were assembled under approximately the same conditions. The special blanket-region fuel elements did not have ribs and were assembled by use of a lower top-end force.

Control and Safety-element Assembly

In many respects the steps in control and safety-element assembly paralleled those of fuel-element assembly. Lower preassemblies were received with T-bar grids on top. Fuel rods were attached to the T-bars, and a hexagonal-tube preassembly was fit over the rod bundle. The hexagonal tube was welded to the lower preassembly to complete the element. Since equipment was not available for the remote assembly of control and safety elements, they were assembled by hand. They were put together in a horizontal position with all components at room temperature.

A control rod in assembly is shown in Figure 14. The lower preassembly has been placed in the fixture and the rod bundle assembled. The technician is shown sliding the hexagonal-tube preassembly over the rod bundle. When in place, the hexagonal tube was welded to the lower preassembly by use of an arc spot-welding gun. Preassemblies for the next control rod are on the table.

Safety elements were assembled in a similar manner with the same assembly fixture. Both control and safety elements were gauged for straightness and straightened as necessary.

106-6726

Figure 14. Control Rod in Assembly

RESULTS

Fuel-rod manufacturing data are given on a batch basis in Appendix A and are summarized in Tables III and IV. The data include the results of all fuel-rod inspections. Of the 14,662 fuel rods assembled, 10,781 were accepted. Almost half of the 3,881 rejects were caused by improper or undefined sodium levels. The fuel pins from all rejected rods were salvaged.

Table III

SUMMARY OF FUEL-ROD MANUFACTURING DATA

Item or Operation	No. Required or Performed	No. Per Acceptable Fuel Rod
Fuel Pins Processed	11,102	1.02
Fuel Pins Reloaded	3,560	0.33
Fuel Rods Assembled	14,662	1.36
Welding Cycles Required	16,483	1.53
Bonding Cycles Required	19,560	1.81
Jacket Preassemblies Required	14,662	1.36
Acceptable Fuel Rods Produced	10,781	1.00
Stripped Pins in Process at Closeout	321	

Table IV

CAUSES OF REJECTION OF FUEL RODS

Cause of Rejection	No. Rejected	Percent
Improper Sodium Level	1,750	45.1
Void in Sodium Annulus	725	18.7
Leak in Closure Weld	626	16.1
Bubble under Restrainer	258	6.6
Trapped Sodium	232	6.0
Other	290	7.5
Total Fuel Rods Rejected	3,881	100.0

Data on the assembly of elements are given in Appendix B. All but 14 of the 55 fuel elements were hand straightened. Acceptance was highest among the special fuel elements which did not have ribs. Only 10 of the 24 elements had to be straightened. Of the 61-rod elements, which were assembled by hand, 50% had to be straightened.

The time expended in manufacturing is itemized in Table V. The 13,387 fuel and simulated fuel rods and the 143 elements were produced over a 15-month period. The job required two engineers, one technical specialist, and eight technicians full time plus some additional part-time help. Six months was spent in setting up and in pilot production of 2,606 simulated fuel rods and 26 simulated fuel elements. Cumulative monthly production for 10,781 enriched uranium fuel rods and loading of 117 fuel elements is shown in Figure 15. This required a total of nine months.

Table V

TIME EXPENDED

Personnel	Man-hours Per 100 Acceptable Fuel Rods	Man-hours Per Acceptable Element(a)	Total Man-hours Required
Engineering	13.0	8.20	2,665
Specialized(b)	13.8	0	1,810
Technician	92.6	9.52	13,263

(a) Assembling the 91-rod elements required approximately twice the man-hours that the 61-rod elements required.

(b) Includes hourly rated, salaried personnel.

Figure 15
Production Rate

106-6729

A log designating the rods placed in each element and their position in that element appears in Appendix C under separate cover.

DISCUSSION

The volume of fuel pins changed during bonding. The structure of the fuel pins received was a metastable one containing some retained, high-temperature gamma phase. The amount was a function of the rate at which the original pin casting was cooled. It varied from pin to pin and from end to end within a pin. When the fuel rods were bonded, most of the retained gamma was transformed to the more dense alpha phase, with a consequent decrease in fuel pin volume. This caused a low sodium level in some rods and accounts in part for the large number of rods rejected for improper sodium level height. Control of fuel-element structure was discussed in ANL-6274.⁽¹⁾

The geometry of the sodium surface was also a problem. The surface was often canted due to uneven feeding during solidification. A canted surface, especially in the vicinity of the restrainer knob, could not be resolved by the eddy-current devices used. In many instances accurate definition by radiography was also impossible. Thus, many rods were rejected because the sodium level could not be defined. This problem was not solved during production of Core I; however, a concurrent study by Cameron and Hessler⁽⁸⁾ at ANL has shown a solution. The surface can be leveled by changing the design of the restrainer to allow more uniform feeding around the knob. The problem can be avoided by measuring the height of a liquid sodium column.

The property termed element "straightness" was not precisely what the term suggests. It was, however, the property desired for proper

reactor operation since it predicts the fit between adjacent elements. The specification of a maximum indicator reading of 0.045 in. could not be met consistently by either hand or remote assembly. In seven cases, the specification could not be met with hand straightening. This showed the need for more precise assembly equipment and a more realistic specification.

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APPENDIX A

The following table summarizes data for fuel-rod manufacturing on a batch basis. The first four columns are included to show the effort required. The next two indicate process efficiency, and the remaining columns point out the causes of rejections of fuel rods.

The data for batch one show that 91 fuel rods were assembled. These required 95 welding cycles, indicating that four of the rods leaked after initial welding and were rewelded.* Since only one rod was rejected for leaks, three of the rewelded rods were leaktight. The 90 leaktight rods required 169 bonding cycles. Approximately 79 rods did not bond acceptably during the first cycle and had to be rebonded. Only 14 were eventually rejected for bond flaws. This indicates that 65 of the recycled rods bonded acceptably. The 76 bonded rods were X-rayed. Forty-six (46) were accepted for reactor use, whereas 30 were rejected for improper or undefined height of the sodium level. The fuel pins in the rejected rods were stripped and recycled.

FUEL-ROD MANUFACTURING DATA

Batch No	Fuel Rods Assembled	Welding Cycles Required	Bonding Cycles Required	Fuel Rods		Cause of Rejection					
				Accepted	Rejected	Leaks	Voids	Bubbles	Traps	Level	Other
1	91	95	169	46	45	1	10	2	0	30	2
2	98	103	147	73	25	2	7	2	0	12	2
3	100	114	156	64	36	1	5	0	0	17	13
4	100	104	190	64	36	2	4	2	0	27	1
5	100	105	130	76	24	0	5	3	0	11	5
6	100	109	203	65	35	6	12	0	0	12	5
7	100	113	180	71	29	5	13	5	0	5	1
8	100	156	115	68	32	9	1	2	0	7	13
9	100	103	168	58	42	0	0	1	2	39	0
10	100	116	134	63	37	12	8	2	1	11	3
11	100	115	149	70	30	5	6	0	1	13	5
12	100	102	134	72	28	1	17	1	0	8	1
13	100	110	122	67	33	7	18	2	0	4	2
14	100	109	114	65	35	5	17	3	0	8	2
15	100	101	123	69	31	0	11	5	0	13	2
16	100	102	112	70	30	2	6	2	7	12	1
17	100	105	180	63	37	1	18	4	0	9	5
18	100	110	169	65	35	9	4	2	3	16	1
19	100	102	122	74	26	2	9	2	2	10	1
20	100	108	117	71	29	5	10	1	3	9	1
21	100	116	116	75	25	8	3	1	1	10	2
22	100	108	114	73	27	2	9	1	4	10	1
23	100	110	133	64	36	5	10	8	1	11	1
24	100	102	139	63	37	2	7	8	0	16	4
25	100	103	139	81	19	0	7	3	0	9	0
26	100	103	138	68	32	4	8	5	0	15	0
27	100	100	135	75	25	1	5	0	1	17	1
28	100	107	148	83	17	6	4	2	1	4	0
29	100	109	131	78	22	7	6	1	1	7	0
30	100	102	137	78	22	2	7	1	3	8	1
31	100	101	148	67	33	1	3	0	2	25	2
32	100	154	126	64	36	13	11	1	0	11	0
33	100	103	131	80	20	3	5	0	2	5	5
34	100	102	183	69	31	2	9	1	0	16	3
35	100	101	131	80	20	2	6	0	2	8	2
36	100	103	136	74	26	2	4	0	8	12	0
37	100	106	122	63	37	3	5	0	3	24	2
38	100	104	141	79	21	6	7	1	2	2	3
39	100	104	151	58	42	3	15	2	4	16	2

FUEL-ROD MANUFACTURING DATA (Cont'd)

Batch No	Fuel Rods Assembled	Welding Cycles Required	Bonding Cycles Required	Fuel Rods		Cause of Rejection					
				Accepted	Rejected	Leaks	Voids	Bubbles	Traps	Level	Other
40	100	105	142	59	41	5	10	0	4	19	3
41	100	105	146	67	33	5	2	2	4	19	1
42	100	101	209	52	48	3	7	2	10	23	3
43	100	111	180	67	33	11	7	6	1	5	3
44	100	102	162	81	19	2	8	0	4	5	0
45	100	102	156	82	18	2	4	2	1	9	0
46	100	105	132	84	16	7	2	0	1	4	2
47	100	103	124	82	18	2	0	3	2	7	4
48	100	104	128	77	23	6	2	0	2	13	0
49	100	105	117	66	34	9	1	2	1	21	0
50	100	155	135	79	21	5	3	0	1	12	0
51	100	103	133	63	37	2	3	3	7	22	0
52	100	118	125	52	48	9	12	0	2	14	11
53	100	137	129	77	23	11	2	1	2	7	0
54	100	103	132	77	23	2	6	0	2	13	0
55	100	102	143	78	22	2	9	0	1	9	1
56	100	102	132	89	11	1	2	1	0	6	1
57	100	103	129	74	26	3	7	0	5	8	3
58	100	145	125	58	42	12	8	0	0	20	2
59	100	101	124	79	21	6	6	1	0	6	2
60	100	102	140	74	26	1	7	3	4	11	0
61	100	101	142	81	19	1	3	1	4	10	0
62	100	100	151	76	24	0	7	3	1	11	2
63	100	100	154	81	19	1	7	3	0	8	0
64	100	102	163	75	25	3	9	4	4	5	0
65	100	103	150	64	36	3	7	2	11	11	2
66	100	105	139	64	36	4	10	1	6	14	1
67	100	107	127	89	11	1	3	1	4	2	0
68	100	104	144	79	21	3	7	3	1	5	2
69	100	100	155	73	27	0	0	5	4	16	2
70	100	107	132	78	22	4	5	2	0	11	0
71	100	101	137	68	32	1	12	1	2	16	0
72	100	100	130	83	17	0	2	2	2	7	4
73	100	102	125	74	26	2	3	1	2	18	0
74	100	105	136	70	30	7	6	2	1	14	0
75	100	101	142	74	26	2	0	1	7	15	1
76	100	103	132	68	32	3	5	1	2	20	1
77	100	102	142	78	22	2	0	1	2	14	3
78	100	100	129	77	23	0	2	1	0	20	0
79	100	106	138	76	24	6	6	1	3	7	1
80	100	101	128	81	19	1	8	3	4	1	2
81	100	137	134	75	25	12	6	2	0	5	0
82	100	109	130	83	17	3	3	1	0	9	1
83	100	116	146	63	37	8	1	7	1	12	8
84	100	127	130	88	12	0	2	1	3	6	0
85	100	116	136	81	19	2	7	0	1	9	0
86	100	133	120	80	20	5	1	1	3	9	1
87	100	109	135	69	31	3	2	1	9	15	1
88	100	126	126	88	12	1	2	0	2	5	2
89	100	131	152	80	20	4	6	3	2	4	1
90	100	117	135	79	21	3	0	2	1	12	3
91	100	101	110	83	17	2	0	2	0	13	0
92	100	161	125	64	36	13	0	0	0	22	1
93	100	132	126	79	21	3	4	1	0	12	1
94	100	119	106	87	13	4	1	0	0	8	0
95	97	126	102	63	34	7	0	0	0	27	0
96	100	108	111	92	8	4	0	1	0	2	1
97	100	126	111	92	8	2	0	0	0	6	0
98	100	122	129	86	14	6	4	2	0	2	0
99	97	122	117	88	9	4	1	0	1	3	0
100	100	129	114	88	12	1	3	0	0	8	0
101	100	138	113	76	24	11	0	0	1	12	0
102	100	122	114	84	16	5	4	1	0	6	0
103	100	135	123	91	9	4	2	0	0	3	0
104	100	114	116	92	8	4	0	2	0	2	0
105	100	111	112	91	9	4	0	3	0	2	0
106	100	114	111	87	13	3	0	5	0	5	0
107	100	117	112	92	8	1	0	0	0	7	0
108	100	105	110	94	6	0	0	2	0	4	0
109	100	108	110	93	7	3	0	1	0	3	0
110	94	110	101	87	7	5	0	1	0	1	0

FUEL-ROD MANUFACTURING DATA (Cont'd)

Batch No	Fuel Rods Assembled	Welding Cycles Required	Bonding Cycles Required	Fuel Rods		Cause of Rejection					
				Accepted	Rejected	Leaks	Voids	Bubbles	Traps	Level	Other
SP1(a)	115	115	148	96	19	0	0	3	8	7	1
SP2	10	10	12	10	0	0	0	0	0	0	0
R1(b)	100	112	121	66	34	10	4	3	3	14	0
R2	100	104	127	65	35	0	8	0	1	25	1
R3	98	100	122	65	33	4	13	1	0	14	1
R4	99	99	129	72	27	0	2	5	1	16	3
R5	100	102	139	60	40	2	10	4	1	23	0
R6	100	100	120	50	50	12	6	0	2	29	1
R7	100	107	124	63	37	7	10	2	2	16	0
R8	100	101	96	58	42	19	8	0	1	14	0
R9	100	102	143	63	37	3	6	2	3	23	0
R10	100	113	211	61	39	10	12	8	1	8	0
R11	99	104	124	83	16	9	4	2	1	0	0
R12	100	104	238	67	33	4	4	15	2	7	1
R13	100	101	146	77	23	2	2	3	6	10	0
R14	100	100	140	69	31	4	6	5	1	15	0
R15	100	110	131	62	38	10	9	7	2	10	0
R16	100	113	133	57	43	3	3	4	2	31	0
R17	100	137	106	77	23	9	3	0	0	8	3
R18	100	141	101	86	14	9	0	0	0	5	0
R19	100	142	128	66	34	5	3	0	2	13	11
R20	100	116	118	83	17	4	3	0	1	8	1
R21	100	112	143	62	38	4	14	0	0	4	16
R22	100	108	132	73	27	3	6	1	0	15	2
R23	100	150	128	65	35	9	5	1	0	16	4
R24	99	115	114	47	52	6	4	0	0	17	25
R25	100	159	99	56	44	14	0	2	0	13	15
R26	100	131	110	69	31	2	0	2	0	15	12
R27	100	115	122	67	33	2	0	0	0	28	3
R28	100	116	107	76	24	8	0	1	0	15	0
R29	100	108	122	75	25	2	2	4	0	16	1
R30	100	127	106	81	19	9	0	1	0	9	0
R31	100	122	109	85	15	2	1	0	0	12	0
R32	100	113	110	72	28	1	1	0	0	16	10
R33	100	109	109	62	38	3	3	0	0	31	1
R34	100	106	122	75	25	2	1	1	0	20	1
R94	100	142	106	81	19	4	1	0	0	12	2
R95	50	68	56	38	12	5	0	0	0	4	3
SPR1	15	15	19	14	1	0	0	0	0	1	0

(a) SP denotes special batch

(b) R denotes reload batch

APPENDIX B SUMMARY

The following is a summary of the fuel-pin inspection log issued separately as Appendix B, Volume I, II, and III. Those elements designated with numbers only were the simulated fuel elements. The letters "B," "D," "L," "S," and "T" designate the blanket region, fuel, control, safety, and boron control elements respectively. The types are listed in the order in which they were assembled.

The letter "G" before the top-end force means that a force greater than that listed was necessary. In most cases, the excess force was applied by impact. The number and depth of the center ribs are given in the table. All but the first five hexagonal tubes also had eight top ribs, 0.050 in. deep.

The indicator readings are given in mils. They are deviations from the readings that would be obtained when gauging a straight element of nominal dimensions. A negative sign indicates a deviation toward the center of an element. Positive readings are deviations away from the element center. The readings designated 1, 2, and 3 were taken on alternate faces of the hexagonal tube, $\frac{1}{4}$ in. down from the top. Readings 4, 5, and 6 were taken on the remaining faces, half way up the hexagonal tube

ELEMENT-ASSEMBLY DATA

Element Assembled	Average Top-end Force (lb)	Temperature		Center Ribs		Indicator Readings (mils)											
		Bundle (°C)	Tube (°C)	No	Depth (mils)	As Assembled						As Straightened					
						1	2	3	4	5	6	1	2	3	4	5	6
1	>175	117	150	11	20												
2	>175	215	349	11	20												
3	>150	117	172	11	17												
4	>175	118	150	11	17												
5	150	118	399	6	20												
6	>175	118	177	8	17	142	-6	-97	0	86	-50	-20	15	-10	30	8	-5
7	175	116	150	7	17	-61	-100	175	27	24	0	<40	<40	<40	<40	<40	<40
8	100	119	166	7	17	112	-4	-196	-4	68	-35	0	-35	26	18	0	15
9	175	118	166	7	20												
10	200	117	200	7	20	165	-29	-225	10	49	-40	42	-16	-39	2	41	6
11	125	119	180	8	20	0	140	-229	-72	84	15	13	16	-44	-15	34	25
12	100	150	180	8	20	7	49	-62	-12	20	45	45	35	40	<40	<40	<40
13	175	121	179	8	25	104	61	-150	-27	89	-24	-5	-7	-18	14	4	25
14	150	118	177	8	25	90	8	-96	4	78	-19	1	18	-17	8	20	22
15(a)	>125	121	192	6	20	51	25	80	-20	60	6	40	43	-90	-30	60	15
16(a)	>175	112	222	6	25	120	86	-500	-37	120	-37	60	-95	63	45	26	12
17	>175	119	214	6	25	45	49	-96	-30	70	9	<40	<40	<40	<40	<40	<40
18	>225	117	176	8	25-20	150	-96	-39	15	90	-42	15	-29	22	15	14	12
19	>225	122	189	8	25-20	45	84	-96	-29	72	0	<40	<40	<40	<40	<40	<40
20	>200	114	185	6	25	70	40	30	-4	-5	57	<40	<40	<40	<40	<40	<40
21	>175	119	376	6	25	94	99	-100	5	49	-8	<40	<40	<40	<40	<40	<40
22	150	118	391	6	22	10	-13	1	6	5	21						
23	>175	119	471	6	25	31	47	-91	-25	49	10	0	-8	-1	0	4	25
24	>175	115	396	6	22	-10	-100	140	70	-55	40	26	-45	15	35	12	2
25	>125	117	421	6	20	-178	-35	-100	14	88	-69	11	3	-12	1	31	12
26	>150	117	388	6	22	26	38	-72	9	40	-4	<40	<40	<40	<40	<40	<40
C-100	105	110	400	6	20	-1	0	16	-6	12	17						
C-101	115	110	400	6	20	-80	40	36	-3	-12	67	-36	24	5	2	0	45
C-102	125	110	400	6	20	-35	-58	91	33	-36	41	-3	-12	5	11	1	24
C-103	175	110	400	6	20	-98	35	40	-31	-2	80	-6	-27	19	-1	-16	28
C-104	165	110	400	6	20	54	-61	-11	0	26	-9	25	-8	-22	10	28	8
C-105(a)	115	110	400	6	20	-52	4	46	-8	65	-21	-11	34	1	1	1	51
C-106	180	110	400	6	20	-78	26	30	-24	-10	69	10	-6	-34	-4	14	23
C-107	155	110	400	6	20	26	-25	-30	17	11	8						
C-108	225	110	400	6	20	-27	34	-43	-20	36	33						
C-109	167	110	400	6	20	22	2	-63	3	21	12	-42	-37	41	23	-25	40

ELEMENT-ASSEMBLY DATA (Cont'd.)

Element Assembled	Average Top-end Force (lb)	Temperature		Center Ribs		Indicator Readings (mils)											
		Bundle (°C)	Tube (°C)	No.	Depth (mils)	As Assembled						As Straightened					
						1	2	3	4	5	6	1	2	3	4	5	6
C-110	155	110	400	6	20	-10	-9	-45	0	21	19						
C-111	135	110	400	6	20	-85	29	0	-16	2	60	-3	-10	-43	0	18	19
C-112	175	110	400	6	20	-88	50	-20	22	23	53	-10	30	-31	-9	22	-30
C-113	180	110	400	6	20	-32	44	-25	-18	12	45						
C-114	145	110	400	6	20	20	2	-36	2	18	14						
C-115	125	110	400	6	20	-18	28	-25	-5	6	40						
C-116	185	110	400	6	20	-64	112	-114	-48	52	38	-19	-2	2	3	4	35
C-117	145	110	400	6	20	100	-46	-77	32	33	-29	-45	-49	30	29	-13	18
C-118	105	110	400	6	20	-42	40	-65	-22	40	24	-55	-12	-18	4	18	20
C-119	135	110	400	6	20	38	-16	-31	6	16	13						
C-120	145	110	400	6	20	-98	100	-11	-55	4	80	-8	20	-40	-8	18	28
C-121	155	110	400	6	20	-24	8	-21	-7	9	33						
C-122	205	110	400	6	20	-58	94	58	-42	32	50	-5	-35	-8	15	3	21
C-123	125	110	400	6	20	-39	35	-34	-15	17	36						
C-124	190	110	400	6	20	-30	85	-83	-48	47	34	-31	16	-25	-10	10	30
C-125	180	110	400	6	20	-25	87	-98	-50	58	35	-25	-25	-16	0	12	22
C-126	165	110	400	6	20	45	-5	-95	0	45	-10	-13	-20	-7	9	5	19
C-127	175	110	400	6	20	-4	36	-98	9	43	9	-32	-24	-7	10	0	22
C-128	140	110	400	6	20	-35	35	-70	-20	22	19	-5	-24	-3	11	-12	20
C-129	140	110	400	6	20	-65	10	26	-5	-20	50	16	0	16	0	-15	40
C-130	160	110	400	6	20	35	10	-10	-1	6	35						
C-131	180	110	400	6	20	41	74	-73	36	35	35	40	20	-41	-16	18	25
C-132	175	110	400	6	20	-37	80	-27	-34	9	60	25	22		-4	5	35
C-133	165	110	400	6	20	35	50	15	-23	-8	60	-3	34	-28	-12	-3	43
C-134	190	110	400	6	20	81	10	-45	-13	30	11	22	24	-17	-16	8	33
C-135	125	110	400	6	20	22	10	-25	-3	15	22						
C-136	190	110	400	6	20	-50	44	4	-20	-6	61	-21	32	-34	-13	-4	40
C-137	105	110	400	6	20	115	-75	-50	30	25	-32	35	-30	-35	13	14	-2
C-138	250	110	400	6	20	17	-7	-40	-3	4	13						
C-139	140	110	400	6	20	-41	-18	29	5	-12	35						
C-140	150	110	400	6	20	-73	80	-30	-40	14	62	-37	34	36	-24	8	38
C-141	165	110	400	6	20	25	-5	-61	-2	17	-2	5	0	-45	-3	2	8
C-142	120	110	400	6	20	-94	23	44	-18	-25	65	-35	-39	32	10	-17	29
C-143	125	110	400	6	20	100	-5	85	0	-30	0	18	-6	-15	8	-30	17
C-144(a)	170	110	400	6	20	-23	62	-46	-17	-17	32	-13	48	-43	-14	-20	28
C-145	180	110	400	6	20	-55	79	28	-46	-20	51	-21	19	-12	-10		32
C-146	120	110	400	6	20	-81	48	28	-19	-100	43	-34	38	-10	-10		36
C-147	125	110	400	6	20	94	94	-64	-38	40	45	-10	40	-30	-8	26	28
C-148	185	110	400	6	20	5	26	-56	5	0	16	0	18	-44	0	32	18
C-149	210	110	400	6	20	-55	49	-35	-15	26	42	-35	21	-40	-3	27	25
C-150	110	110	400	6	20	4	55	-77	20	43	18	17	3	8	1	9	31
C-151	100	110	400	6	20	-94	55	8	-22	9	65	-45	12	-15	-2	20	32
C-152	230	110	400	6	20	-47	70	-63	-24	40	30	-37	12	-16	1	20	25
C-153	135	110	400	6	20	-28	44	-60	-11	36	28	-47	5	-13	4	12	28
C-154	125	110	400	6	20	5	55	75	-20	34	40	-45	2	-36	0	24	20
B-300(a)	80	110	400	6	20	-95	-25	100	8	55	52	-40	-12	48	4	-28	26
B-301	165	110	400	6	20	67	10	-87	-10	38	-24	45	-16	-47	2	18	-18
B-302	125	110	400	6	20	4	-98	89	45	-33	4	12	-35	11	16	0	0
B-303	150	110	400	6	20	5	-23	10	4	6	0						
B-304	170	110	400	6	20	-14	-82	87	48	-30	35	-25	-16	29	15	-7	36
B-305	120	110	400	6	20	26	16	-51	0	35	8						
B-306	135	110	400	6	20	-39	-43	75	25	-21	40	0	-12	1	11	10	21
B-307	130	110	400	6	20	-28	77	-59	34	48	31	-15	34	-30	-15	28	27
B-308	105	110	400	6	20	-85	77	5	-22	8	51	-25	34	-17	-6	-16	21
B-309	145	110	400	6	20	-74	-50	112	30	-37	42	-32	-20	39	19	-12	4
B-310	150	110	400	6	20	0	-25	100	-20	-40	30	14	15	0	8	1	-8
B-311	185	110	400	6	20	-86	-26	139	30	-55	30	-25	-13	25	18	-10	-2
B-312	155	110	400	6	20	27	58	-93	-19	52	-30	-24	37	-18	-9	15	-8
B-313	110	110	400	6	20	-40	-10	38	12	-12	3	-40	-10	38	12	-12	3
B-314	95	110	400	6	20	-27	3	15	11	2	-12						
B-315	175	110	400	6	20	-95	34	60	-7	-15	22	-45	3	38	8	-8	-5
B-316	155	110	400	6	20	95	70	70	-23	-35	42	-50	25	12	5	-10	-2
B-317	175	110	400	6	20	-65	80	-25	-39	20	0	0	1	-16	-5	15	-27
D-350	175	110	400	6	20	4	26	19	20	0	-43						
D-351	75	110	400	0		-65	12	45	0	4	42		12	45	0	4	42
D-352	75	110	400	0		-55	-49	107	44	-38	38	24	5	-29	15	25	-48
D-353	75	110	400	0		-40	-20	50	15	0	-36						
D-354	75	110	400	0		-36	32	-10	-6	27							
D-355	75	110	400	0		-38	8	8	3		28						
D-356	60	110	400	0		-47	-25	60	15	-6	40						
D-357(a)	75	110	400	0		-65	-7	54	2	-15	45	-7	54	2	-15	45	
D-358	75	110	400	0		-24	3	5	0	22	25						

ELEMENT-ASSEMBLY DATA (Cont'd)

Element Assembled	Average Top-end Force (lb)	Temperature		Center Ribs		Indicator Readings (mils)											
		Bundle (°C)	Tube (°C)	No	Depth (mils)	As Assembled						As Straightened					
						1	2	3	4	5	6	1	2	3	4	5	6
D-359	75	110	400	0		78	-98	26	50	2	14			-20	25	21	-5
D-360	75	110	400	0		20	-6	-26	0	34	0						
D-361	75	110	400	0		-23	-31	36	12	-4	30						
D-362	75	110	400	0		-95	82	25	46	0	84		11	27	-10	-2	48
D-363	75	110	400	0		15	-15	-17	12	22	5						
D-364	75	110	400	0		-60	-22	45	20	-18	43	-31	-28		25	-9	30
D-365	75	110	400	0		4		-28	-2	22	11						
D-366	75	110	400	0		-48	40	-15	-5	26	35						
D-367	75	110	400	0		-25	2	9	14	5	22						
D-368(a)	75	110	400	0		-94	70	11	-33	1	67		45	1	-16	10	52
D-369	75	110	400	0		-60	5	35	9	-15	45						
D-370	75	110	400	0		-57	10	32	0	-6	48						
D-371	75	110	400	0		0	65	82	-24	46	25	-10	25	29	-3	20	28
D-372	75	110	400	0		-30	-5	18	14	-3	25						
D-373	75	110	400	0		-38	-48	62	29	-20	30	-32	-35	44	24	-15	30
L-400						16	21	-16	21	-3	-11						
L-401						-45	25	-14	-13	2	22						
L-402						35	-47	-28	4	8	-2						
L-403						21	36	16	-20	35	-4	-11	20	13	-21	22	2
L-404						-21	27	-21	-7	2	7						
L-405						-6	-16	-1	12	4	-14						
L-406						1	49	35	1	-17	24	-6	-41	24	8	-8	24
L-407						-196	-182	-134	-84	55	-17	-34	-3	15	25	7	-26
L-408						9	-13	-24	20	-2	-11						
L-409						56	-48	-40	-2	15	-7	37	-48	-2	0	1	4
L-410						-31	55	-64	-8	34	2	40	10	8	-3	11	9
L-411						-54	12	23	10	-7	32	11	-25	-17	22	-8	4
L-412						-54	39	-24	-34	8	32	12	-33	-9	-10	0	15
L-413						3	-15	-28	18	0	-12						
S-600						-9	-5	-7	11	15	7						
S-601						-42	1	4	22	-5	-4						
S-602						-42	26	-36	25	3	-15						
T-500						-113	-29	140	-3	-50	50	18	-44	8	5	0	-1
T-501						100	-116	22	25	0	-20	-30	16	11	-13	2	20
T-502						-19	25	-39	14	-12	0	14	43		0	12	15

(a) Fuel rods out of tolerance as straightened

APPENDIX C

Appendix C is a complete loading record showing the position, loading sequence, Special Materials batch number, Metallurgy melt number, casting number, net weight and net weight of each fuel rod loaded into every fuel element. Special rods are designated and their positions marked. The loading record also shows total fuel weight, calculated weight of source and fissionable material and calculated U^{235} content for each fuel element. The type of fuel element, whether core, blanket core, special blanket, control or safety element is indicated. Copies of Appendix C have been distributed as follows: F. G. Foote, R. E. Macherey, A. B. Shuck (2), L. J. Koch (2), H. O. Monson, M. Novick (2), S. Lawroski, M. Levenson, L. K. Hurst, J. H. Kittel, Laboratory Director's Reading File.