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GEAP-13713

AEC RESEARCH AND DEVELOPMENT REPORT

JUNE 1972

INSTRUMENTED FUEL ASSEMBLY FABRICATION REPORT

COMPILED BY
E. CRAIG et al

U.S. ATOMIC ENERGY COMMISSION
CONTRACT AT(04-3)-540

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Prepared for the
Southwest Atomic Energy Associates
for Transmittal to the
United States Atomic Energy Commission
Under Contract Number AT(04-3)-540

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1. INTRODUCTION

The Southwest Experimental Fast Oxide Reactor (SEFOR) is a 20 MWt fast-spectrum reactor fueled with $\text{PuO}_2\text{-UO}_2$ and cooled with sodium. The reactor characteristics are similar to the large, soft spectrum fast breeder reactors fueled with mixed $\text{PuO}_2\text{-UO}_2$. It is being used to obtain physics and engineering data at fuel compositions, temperatures, and crystalline state characteristic of power reactor operating conditions. SEFOR is particularly designed for the systematic determination of the Doppler coefficient of reactivity at temperatures up to the vicinity of fuel melting.

The project consists of two major parts: the design and construction of the reactor and a related research and development program. Funds for the design and construction of the facility were provided by the Southwest Atomic Energy Associates (a group of 17 investor-owned utility companies located in the South and Southwest parts of the United States), together with the Karlsruhe Laboratory of West Germany, Euratom, and the General Electric Company.

The United States Atomic Energy Commission is supporting the Research and Development (R&D) Program. The R&D Program consists of two phases:

Phase I— Preoperational Research and Development

Phase II— The Reactor Test Program after the start of reactor operation

This report describes work performed in Phase I of the Research and Development Program under Task 9, Fuel Fabrication.

The work included the fabrication of Instrumented Fuel Assemblies (IFA) for the first core of SEFOR.

The Instrumented Fuel Assembly (see Figure 1-1) houses thermocouples to measure fuel and coolant temperatures and a magnetic flowmeter to measure coolant flow rate through the assembly. The assembly consists of two instrumented fuel rods and a center BeO-filled tightener rod. The three rods are attached at both the top and the bottom to form an integral unit. The overall length of the assembly, including the lead connector at the top is 12 feet 4 inches. Four regular fuel rods are loaded in the same core channel with the instrumented fuel assembly to complete the normal fuel assembly loading of six rods and a center BeO-filled tightener rod. The two instrumented fuel rods each contain two tungsten/rhenium thermocouples positioned at the centerline of the fuel pellet—one located at midplane of the core and the other at the axial position closer to the top of the core (at a position which is approximately 75% of the average power density).

The work also included fabrication of handling fixtures required to transport and install the instrumented fuel assemblies in the reactor core.

Previous development work on the IFA's, electrical connectors and fuel thermocouples is described in References 1 to 5. Functional requirements (e.g. time response, allowable measurement uncertainty) are described in Reference 1 and further detailed in Reference 6.

Figure 1-1. The 'Instrumenta' Fuel Assembly in the Transport Fixture

2. FABRICATION AND ASSEMBLY OBJECTIVES AND DESCRIPTION

2.1 GENERAL REQUIREMENTS

Instrumented fuel assemblies were designed to obtain information necessary to verify the physics and thermal analysis calculations of the core behavior during the planned tests. To accomplish this objective, a number of core parameters were to be monitored during startup, steady-state, and transient core operation.

The sensors and associated components making up the instrumented fuel assemblies will operate under both steady-state reactor operation (0 to 20 MWt) and power transients up to 1.0×10^4 MWt. The fuel temperature will be up to 4500°F and the cladding temperature will be up to 1000°F during these tests.

The test program was planned for three years of operation. High reliability from both design and fabrication was required in order to attain an operating life time of this duration in an environment of high-temperature sodium and reactor-core radiation level.

The completed IFA in the assembly fixture is shown in Figure 2-1. This assembly was designed to be inserted into a peripheral fuel channel.

2.1.1 Fuel Center Temperature Sensor

Two rods per assembly, two thermocouples per rod were used for fuel temperature readout (see Figure 2-2). Tungsten/rhenium thermocouples were located at the center of the fuel pellet at the peak flux and at the position of 75% average flux.

2.1.2 Channel Inlet and Outlet Temperature Sensors

Chromel/alumel thermocouples are located above and at the bottom of the fuel zone in the channel sodium flow. Two thermocouples are above the core, at the core outlet, and one thermocouple is located at the bottom of the core, at the coolant inlet (see Figure 2-3).

Figure 2-4 shows the thermocouple pass-through sleeve in place and the coolant inlet thermocouple as it extends from the sleeve and tightener rod into the coolant flow path. This flow path is bounded by the tightener rod and two adjacent fuel rods in the core channel.

2.1.3 Channel Flow Sensor

The magnetic flowmeter (Figure 2-5) is located on the end of the instrumented fuel assembly and extends through the core support plate when inserted in the reactor core. The flowmeter measures channel flow at inlet core coolant conditions. The throat of the flowmeter is sized to provide the same flow restriction as a normal channel flow orifice in the same core flow zone.

The ring magnets (Alnico VI) shown in Figure 2-6 were stabilized at 1000°F prior to assembly in the flowmeter. The notches in the magnets allow for lead cable passage and are keyed to retain the rings from rotation.

An exploded view of a partially completed flowmeter is shown in Figure 2-7. The inner shell has been welded to the body of the flowmeter. The flame-sprayed alumina can be seen on the inner shell.

2.1.4 Instrument Lead Connector

To provide maximum reliability for the instrumented fuel assemblies in the SEFOR core, the instrument lead and connector system remain undisturbed while the reactor vessel refueling head is removed and any regular fuel rod changed. This design operates inside the reactor vessel, sealed from the sodium and sodium vapor, during reactor operation.

The connector flange which is mounted inside the reactor vessel to mate with an IFA is shown in Figure 2-8. This flange contains a female 20-pin electrical connector.

Figure 2-1. Instrumented Fuel Assembly in the Final Assembly Fixture

Figure 2-2. Instrumented Fuel Assembly

Figure 2-3. Coolant Inlet Thermocouple

Figure 2-4. Coolant Inlet Thermocouple Extending from the Tightener Rod End Plug

Figure 2-5. Magnetic Flowmeter

Figure 2-6. Flowmeter Ring Magnets

Figure 2-7. Flowmeter Exploded View

Figure 2-8. Vessel Internal Connector Flange

The pin connector flange of the completed pressure vessel portion of the IFA is shown in Figure 2-9. The precision dowel pins are shown on the flange. The flange bolts are captured.

2.2 SPECIFICATIONS

2.2.1 Materials

The materials selected for use in the regular noninstrumented fuel rods for SEFOR were also used in the fabrication of instrumented fuel assemblies. This also included material selected for the tightener rod and the tightener rod sleeve. The following list of materials is not complete but serves as an example explaining some of the study effort used to arrive at selections and quality control requirements.

2.2.1.1 Cladding Tube—End Plugs

The tubing used for fuel rod cladding was Type-316 stainless steel (SS). In fabrication of fuel rods, this cladding was welded to Type-304 stainless steel end plugs and segment bulkheads. The Type-316 SS selected had the highest available Cr/Ni ratio, Mo and Si content within commercial limits. The Type-304 SS selected also had the highest available Cr/Ni ratio within commercial limits. The presence of ferrite in the base materials was found to minimize susceptibility to cracking in the weld zone and therefore provided more favorable conditions to achieve sound welds. The Type-316 SS cladding was preferred over Type-304 SS because of the higher strength. The cladding is the most highly stressed component of the fuel rod.

2.2.1.2 Sensor Lead Cable Sheath

Inconel 600, ASTM SB-163 annealed tubing was selected for sheath material over Type-304 stainless steel. The comparison study of thermal expansion properties of the sheath, the ceramic insulation and sensor lead wires lead to the Inconel 600 selection.

The Inconel grain size was controlled to prevent the possibility of one grain boundary extending from the inside to the outside of the wall thickness. It was found necessary to minimize process grain growth by limiting the time at brazing temperature (2150°F) to a few seconds. This applied to all joints between the sensor lead sheath and other instrumented fuel assembly components.

2.2.1.3 Tungsten/Rhenium Thermocouple Wire

Due to the tendency of tungsten/rhenium wire to have defects, a special effort was carried out to obtain defect-free wire. The wire was certified as to calibration and was tested for homogeneity by passing the individual wires through a temperature gradient of approximately 1000°F/in. in an inert atmosphere. A signal greater than ±50 microvolts was cause for rejection of a portion of wire (see Figure 2-10).

2.2.1.4 Beryllia Insulator Beads

The impurities were held to a minimum in the insulators to reduce the tendency of high temperature chemical action and to prevent degrading the melting point below 4500°F. A melting point temperature acceptance test was performed.

2.2.2 Welding

The weldments used in the various components of the instrumented fuel assemblies represent some of the most critical operations in the fabrication process because these welds are the most likely source of component failure, permitting either entry of liquid sodium or emission, for example, of plutonium, fission gases or beryllium oxide.

All configurations were welded successfully, but not without difficulties.

Figure 2-9. Connector Flange of the Assembly

Figure 2-10. Homogeneity Test on Tungsten/Rhenium Wire

2.2.2.1 Tube-to-Spacer Welds

A lip weld was developed for the fuel rod and associated components. A basic advantage of a lip weld is that it offers precise alignment of the components and provides adequate metal for the fusion welding technique (which eliminates the use of filler metal). An additional requirement of the design was to produce as uniform a wall transition as possible between welded components in order to minimize thermal stresses introduced during thermal transient reactor tests.

The initial design required a lip 30 mils in length and 15 mils thick (i.e., a 40-mil wall tubing was press-fitted over a 15-mil lip of a 55-mil wall plug). The development effort resulted in determining the proper current and rotation time to ensure full penetration (see Figure 2-11).

The weld specification required destructive testing of sample welds to demonstrate the process and the operator qualification. A trial weld produced prior to a days production effort was examined for indication of continued high quality weld joints.

2.2.3 Brazing

Braze development and arriving at final braze specifications required a considerable effort. An ASME specification for brazing qualification procedure was developed. Other braze joints were not in the Code section of the assembly but were specified to the intent of the Code.

Some of the braze joints were internal to the assembly with no contact with sodium. Other braze joints were exposed to sodium on one side and provided a containment barrier for the instrumented fuel assembly. The containment brazes were all high-nickel type brazes (Nicro Braze Numbers 30 or 50). (See Figure 2-12).

2.2.3.1 Transition Sleeve Joints

The specification for brazing the Tungsten/5Rhenium (W/5Re) wire to the Ni5Cu wire in the transition sleeve of the fuel thermocouple involved the use of a two-step or two-temperature braze sequence with a nickel ribbon splice piece. The combination of palladium-nickel and copper brazes was used for these joints (see Figure 2-13).

2.2.3.2 Flowmeter Lead Tightener Rod Joint

Visual observation of this joint during the braze melt operation was a required specification for success on this braze. To achieve this objective, an intermediate sleeve long enough to allow two separate brazes without remelt of the first, was used. The end plug-to-sleeve braze was made with Nicro Braze Number 30 and the sleeve-to-sheath braze was made with Nicro Braze Number 50.

2.2.3.3 Seal Block Lead Joint

Following extensive development effort using various "forming gas" atmospheres and torch brazing methods a successful hydrogen atmosphere braze was developed for the seal block-to-lead joint. The specification required limiting the time at braze temperature to between 10 to 20 seconds. The grain growth and alloying of the parent metal were controlled by limiting the time at braze temperature.

2.2.3.4 Bulkhead Lead Joint

Two bulkhead-to-lead joints were made on each instrumented fuel assembly. One bulkhead on the ASME Code Section was made following the approved Brazing Qualification Procedure EA-21. The other bulkhead braze (Part 20 Figure 5.3) specification was similar to the Code Braze. Both brazes were made with Nicro Braze Number 30.

2.2.3.5 Tightener Rod Thermocouple Joint

After considerable development, a specification was established requiring the braze to be made to the intermediate sleeve after the sleeve was welded into the tightener rod. The sleeve was machined to be flush on the inside prior to the weld. The specification required a Nicro Braze Number 50 to be made in a hydrogen atmosphere.

Figure 2-11. Tube-to-Spacer Weld Setup

Figure 2-12.
Brazing the Leads Coming from the Upper Housing

Figure 2-13. Thermoelement to Nickel Spiral to Lead Out Wire

2.2.4 Leak Detection

The assembled flowmeter, tightener rod housing, pressure vessel, and splice region compartments were each given a mass spectrometer leak check. The specification required a leakage rate of less than 4×10^{-8} standard cc/sec of helium at 1 atmosphere differential pressure. A standard leak of 4.6×10^{-8} was used to calibrate the leak detector.

Leak detection tests of subassemblies were required after each assembly braze or weld operation. These tests were followed by a final leak check of the region compartments.

2.2.5 Assembly

The instrumented fuel assembly was fabricated to GE Specification 22A1666. The specification was used to define critical or limiting aspects of the assembly procedure. This specification included a sample quality control check sheet which was expanded in scope during the work effort.

The critical and limiting aspects of this assembly were similar to other reactor core components. Since the fuel rods were fabricated to a different specification (22A1650), it was possible to delete from this specification the critical or limiting aspects of the fuel and fission gas containment.

2.2.6 Cleaning

Assembly parts made-up entirely of stainless steel were cleaned to GE Specification P4CYP3-S1 and followed by passivation to GE Specification P4AYP1-S-2. Subassemblies, as well as single parts, were cleaned to this specification. Materials other than stainless steel involved as parts or subassemblies were cleaned with acetone.

The GE Thermocouple Process Specification 21-A-2332 required braze areas to be cleaned by blasting with aluminum oxide.

2.2.7 Quality Control

A Quality Assurance Program was developed and implemented. Part of this program was already in existence under the existing Shop Operations Operating Procedures. This base was then expanded to cover all the necessary phases required by instrumented fuel assemblies. This quality assurance program covered the obtaining and documenting of incoming material certifications through the final outgoing quality inspection.

The following list delineates those quality control items which were utilized in the fabrication of the SEFOR instrumented fuel assemblies.

Material certification papers were required on all materials used in the fabrication of thermocouples, fabricating parts for the fuel and other pressure containments. Material certification papers were checked to assure accuracy and completeness. They were then filed so that a master file was established. The material certifications consisted of:

- a. Material composition and heat numbers applicable;
- b. Mechanical properties as determined by quantitative tests;
- c. The results of special tests such as leak check, x-ray, ultrasonic, etc.

Inspection reports were required for:

- a. Incoming parts inspection;
- b. In-process inspection;
- c. Finished parts and subassemblies inspection;

- d. Special inspections such as determining straightness of the fuel rods;
- e. Final outgoing dimensional inspection.

These reports were made by the machine shop inspectors. A master file of inspection reports was established which contained all inspection reports. This file has become a portion of the master file.

Signoff sheets were implemented in accordance with the established procedures. These sheets also provided a sequence for the fabrication steps. Two forms of signoff sheets were established.

An Assembly Sequence Diagram (ASD), was used in the fabrication of the fuel thermocouples. The ASD had major milestones indicated, such as braze, leak check, continuity check, etc. After each operation, that checkpoint was initialed by the cognizant technician.

The second signoff sheet was the Quality Control Certification Card. This was a detailed assembly sequence diagram for the fabrication of the instrumented fuel assembly. These cards have satisfactorily served as documentation for the assembly of the IFA's.

Both of these types of signoff sheets were filed after completion. Copies were reviewed by Engineering personnel upon completion of each IFA.

Weld and Braze Process Qualification criteria were established for each Coded or vital joint. This involved the welding of the tightener rod segments, fuel rod extension tubes and the coded pressure vessel portion. The brazes of primary concern were the seal block area, the thermocouple pass-through sleeves in the tightener rods and the thermocouple weldment area.

The final desired results or criteria were established as to penetration, porosity, embrittlement, etc. The process was developed whereby it could repeatably produce the necessary results. When a satisfactory process was developed, the process was standardized and used thereafter.

In several instances, preweld and postweld samples were required to assure the reliability of the process. One such area was the fuel rod-to-fuel extension rod welds made on the glass lathe. Satisfactory samples were made both before and after the actual welds.

Technicians were qualified, in conjunction with the establishing of weld and braze qualifications, to perform the critical welds and brazes using the approved procedures. The weld process was established and the welder (technician) qualified together. Records authorizing certain technicians to perform specific welds and brazes are on file.

A technician having a current ASME Code qualification certification made the pressure vessel welds. A record of his certification is on file.

A number of special quality control measures was instituted to assure a high quality product. The results of these tests and checks are documented as to either the actual results, x-ray films, or by having the responsible technician and/or engineer signoff the Quality Control Certification Card.

The following is a representative list of the special tests and quality control measures employed by the Irradiation Processing Operation (IPO) Shop:

- a. X-ray and neutrography
- b. Mass spectrometer leak checks
- c. Electrical resistance checks

- d. Electrical continuity checks
- e. Thermocouple thermal cycling and calibration
- f. Special thermocouple test of the pressure vessel leadout wires
- g. Pneumatic pressure test of the pressure vessel portion
- h. Heat source check of the fuel thermocouples
- i. Microscopic examination of the tungsten/rhenium thermoelement wires
- j. Thermocouple phasing
- k. Metallurgical examination of welds and brazes
- l. Use of special equipment, tools and fixtures to guarantee dimensional alignment and accuracy.

Deviation reports were instituted to document deviations in the product or in processes. The deviation report was compiled by the IPO Shop and approved by Engineering. The deviation reports became a permanent record of that IFA.

Engineering change notices were processed through the Manufacturing Project Engineer.

Final inspection of the instrumented fuel assembly was conducted just prior to packaging and shipment. This inspection consisted of an overall dimensional check as well as a thermocouple resistance and continuity check. One of the significant dimensional checks was that of the alignment of the electrical pin connectors. The results of this inspection were documented by the issuance of an inspection report which became a permanent record of that instrumented fuel assembly.

3. COMPONENT DESCRIPTION

3.1 CASTING MACHINE PART—SPIDER

3.1.1 Description (Function)

The support spider (Figure 3-1) acts as a spacer and centering device for the fuel rods and the instrumented fuel assembly inside the core channel. The spider retains the fuel rods, the tightener rod, and the flowmeter.

3.1.2 Casting for Spider

3.1.2.1 Form

The spider has six connecting legs surrounding a center hub designed to occupy a minimum volume in the core channel. The same base casting was used for two different part requirements. One application was for the IFA and the other was for the regular core tightener rod assemblies. The total requirements for the reactor were 112 castings.

3.1.2 Material

The material used in the casting was ASTM-A2351-CF8, Type-304 stainless steel.

3.1.3 Machining Spider

Interface machining only was required. Holes were drilled for interface with the fuel rods in the top of the six spider legs along with a corresponding sodium drain hole. The hole in the hub interfaces with the tightener rod. Projections were machined on the bottom of the spider legs for the flowmeter interface. The ears on the periphery of the spider were machined to interface with the core channel.

3.2 FORGING-MACHINE PART

3.2.1 Flange, Conoseal, Remote Operable

3.2.2 Description (Function)

The flange (Figure 2-9) forms a junction point for the IFA inside the reactor vessel near the vessel nozzle penetration of the reactor outer head. The flange provides interchangeability, remote operation and a cover-gas seal barrier for the 20-pin connector welded internally to both flanges. The male (lower) flange (Figure 2-8) is attached to the vessel outer and has a slotted tube extending down approximately 16 inches from the top of the flange to act as a positioning guide for the mating instrument fuel assembly. The female (upper) flange is welded to the IFA and has a lifting lug welded to the top surface. A Conoseal gasket is retained on the upper flange and mating with the lower flange provides the sealing barrier against sodium vapor in the argon cover gas contacting the 20-pin connector. The flange mating operation is accurately guided by tapered pins as the two captured flange bolts are tightened. The bolts with Belleville washers secure the flange joint.

The flanges were fabricated and inspected in accordance with the ASME Code Section III.

3.2.3 Forging for Flange

3.2.3.1 Form

The flange has an unsymmetric shape to allow clearance for the fuel grapple and to provide for passage through a hole in the steel shield above the reactor core. The shape also provides for the placement of the two flange bolts in accessible positions.

3.2.3.2 Material

The flange forgings are ASTM-A-182 GRF Type-304 stainless steel.

Figure 3-1. Support Spider (Casting)

3.2.4 Machining

Machining of all surfaces was required. Holes were drilled for interface with guide pins. Gasket seats were machined for interface with the Conoseal gasket. Holes were drilled and tapped for interface with the flange bolts.

3.3 BAR AND TUBING MACHINE PARTS

3.3.1 Bar-Bottom End Plug

3.3.1.1 Description (Function)

The bottom end plug (Figure 2-11) is welded to the tightener rod tube making a leak-tight unit on one end, and welded to the spider on the other end, making the rod assembly an integral part of the IFA. A penetration of the end plug was required for the inlet coolant thermocouple and a second penetration was required for the flowmeter lead.

3.3.1.2 Material

The material used for the end plug was ASTM A-276 Type-304 stainless steel bar stock.

3.3.2 Tubing—Fuel Cladding

3.3.2.1 Description (Function)

The fuel cladding is used to contain the fuel pellets between spacer couplings or between a spacer coupling and an end plug. The tube interfaces with and is welded to the spacers and the end plugs (see Figure 3-2).

3.3.2.2 Material

The material used for the fuel cladding was ASTM A-269 Type-316 stainless steel with additional requirements such as ultrasonic inspection.

Figure 3-2. Completed Fuel Rod G1-2

3.4 FORMED AND PUNCHED PARTS

3.4.1 Lead Wire Shield

3.4.1.1 Description (Function)

The lead wire shield provides a protective structure for the thermocouple leads (Figure 3-3). One end of the shield is welded to the main housing and the bottom is welded to the support guide. The shield is made from perforated sheet with elongated slots to allow the passage of sodium. Two perforated sheets were resistance-welded to a rectangular strip at the top adding rigidity to the weldment.

3.4.1.2 Material

The perforated sheet was made from ASTM A-240 Type-304 stainless steel.

3.5 THERMOCOUPLES AND LEAD CABLE

3.5.1 Coolant Thermocouples

3.5.1.1 Description (Function)

With the thermocouples located in the sodium coolant channel stream, before and after the reactor core, it is possible to monitor a particular fuel channel for coolant temperature increase or, if coolant flow is considered, channel power may be determined. The thermocouples are required to operate in the liquid sodium environment under steady-state and transient conditions from 400°F to 1000°F. The time constant for the thermocouples will be less than 0.1 second.

The coolant thermocouple extends into the coolant path as explained in Paragraph 2.1.2. The inlet thermocouple passes through the reactor core confined in a hole made-up by the annular BeO pellets in the tightener rod. After forming an expansion loop in the upper housing the lead cable leaves the housing through a pass-through sleeve as shown in Figure 2-12.

The lead cable follows a zigzag course as shown in Figure 3-4 to the edge of the core where it enters an expansion loop. A vertical path from the expansion loop enters the pipe section through a bulk head braze. Between the bulk head braze and the Code pressure vessel section a splice is made in each lead (see Figure 3-5).

The lead cable passes through the pressure vessel section ending in the 20-pin connector as shown in Figure 3-5.

From the female connector in the vessel internal connector flange shown in Figure 2-8, the sheathed lead extends from the top of the outer head through a potted section (just below the square box shown on nozzle extensions in Figure 3-6). The lead cables lead the nozzle box in a bundle and are carried out through the refueling cell and to a second potted seal at the constant temperature junction box in the reactor operation-accessible area outside the refueling cell.

3.5.1.2 Materials

The Inconel 600 ASTM SB-163 sheath has similar expansion properties to Hoskins Type 3-G 179 chromel/alumel wire. Magnesia with a density of 85% to 88% of theoretical will match expansion properties of the chromel/alumel wire. It will at the same time prevent the gripping action between wire and sheath experienced in high density, insulated, sheathed thermocouples.

In two of the assemblies dummy coolant thermocouples were installed. These have two alumel legs.

Figure 3-3. Lead Shield

Figure 3-4. Lead Cable Zigzag Course and Expansion Loop

Figure 3-5. Code Pressure Vessel Section Exploded View

Figure 3-6

Lead Cable Exit from the Reactor Vessel

3.5.2 Fuel Thermocouples

3.5.2.1 Description (Function)

The fuel thermocouples provide a means to measure fuel temperature up to the vicinity of fuel melting (approximately 4500°F) which is the planned operating limit for the fuel in SEFOR. The fuel thermocouples will have small response times compared to the heat transfer time constant of the fuel rod (approximately 30 seconds).

Experience from previous programs indicated it was feasible for the design conditions to be met; however, additional information was needed to properly design and determine specifications for the thermocouples. An extensive program, involving both in-pile and out-of-pile testing, was carried out to obtain the necessary information. (References 3, 4 & 5)

The following thermocouple designs were selected for use in the SEFOR fuel elements based upon the experimental results from the SEFOR program and the work of other programs. The wires selected are W5Re/W26Re, and the sheathing is W26Re. Some of the thermocouples use BeO insulators and the remainder use ThO₂. Three different junction sizes were used (shown on Figure 3-7):

0.140-in. o.d. sheath with 0.010-in. wires,

0.063-in. o.d. sheath with 0.005-in. wires,

Bare 0.010-in. wires.

Dummy thermocouples having both wires made of W26Re will be used in 2 of the 24 fuel thermocouple positions in the core. The signal from leads will be a result of gamma radiation induced electron flow, systematic material and temperature gradients in the connector, and the signal generated from the electromagnetic field induced by a neutron flux transient. Similar alumel, alumel-dummy thermocouples will be used in the coolant region as described in Paragraph 3.5.1.2.

All fuel thermocouples are located in the fuel rods as shown in Figure 2-2. Lead out wires (Ni5Cu and Ni20Cu) are compensated lead for the W5Re, W26Re thermoelements. This compensation is good up to 1000°F lead temperature.

The junctions or splices between the thermoelements and the lead wires are made with an intermediate spiral nickel ribbon. The wires are brazed to each end. The spiral ribbon shape allows for thermal expansion without significant stress in the thermocouple wires.

The leadout cable leaving the top of the fuel rod passes through the extension rod confined in a hole made by the annular steel pellets. In the upper housing the lead cable joins the coolant thermocouple and flowmeter lead cable and continues out to the data acquisition system as described in Paragraph 3.5.1.1.

3.5.2.2 Materials

3.5.2.2.1 Tungsten/Rhenium Tubing

The tungsten/rhenium tubing used for the thermocouple sheath in the fuel region was of high quality with the following being a typical analysis:

Billet Number 26151 (0.062 o.d. X 0.042 i.d.) is 99.98% pure.

Figure 3-7. Fuel Thermocouples

Spectrographic Analysis:

Impurities— Total detected—0.016% (160 ppm)

	ppm		ppm		ppm
Mo	150	Si	10	Ti	<20
Ni	5	Sb	<10	Co	<5
Al	5	Fe	<1	Ag	<0.1
Cu	0.5	Mn	<0.1	Mg	4
Ca	5	Pb	<10	Ta	<100
Cr	<5	Sn	<10	Nb	<100
Ba	<5	Bi	<1	Zn	<300
Be	<0.1	V	<10	Zr	<10
B	<10	Na	<50		

Chemical Analysis:

W - 74.9%
 Re - 25.1% (by difference)

The microstructure exhibited longitudinally oriented grains with less than 10% equiaxed recrystallized grains, and a transverse section exhibited an apparent grain size of ASTM-5 or smaller. The tubing passed a bend test at 20°C by bending around an arbor of 0.75 in. radius for 45 degrees without fracture.

3.5.2.2.2 Tungsten/Rhenium Wire

The WRe thermocouple wire was premium grade, calibrated and tested for homogeneity.

3.5.2.2.3 Insulators

The high temperature portions of the thermocouples were insulated with either thorium dioxide or beryllium oxide.

The thoria had a density greater than 8.1 gm/cc. The purity was greater than 99 wt % with the balance of impurities less than indicated below:

	ppm		ppm		ppm
Al	2000	K	50	Si	1000
B	10	Li	100	Sr	10
C	30	Mg	400	Ti	10
Ca	500	Mn	5	V	10
Cr	20	Na	50	Zn	50
Cu	10	Ni	10	Zr	50
Fe	50	S	30		

The beryllia had a density greater than 2.6 gm/cc. The purity was greater than 99 wt % with the balance of impurities less than indicated below:

	ppm		ppm		ppm
A1	1000	K	20	Si	500
B	5	Li	2	Sr	10
C	20	Mg	2000	Ti	10
Ca	200	Mn	10	V	10
Cr	10	Na	70	Zn	20
Cu	5	Ni	10	Zr	50
Fe	30	S	20		

The transition portion of the thermocouple was insulated with 99.5% pure aluminum oxide with less than 0.12% silicon dioxide. The sum of boron and cadmium did not exceed 30 ppm, sulphur did not exceed 5000 ppm. The alumina was a minimum of 90% theoretical density. The same quality of alumina insulators was used for the beads on the expansion section of the bare wire thermocouples.

The transition sleeve was made of Inconel 600 ASTM SB-166 in a cylinder shape.

3.5.3 Flowmeter Lead Cable

3.5.3.1 Description (Function)

The flowmeter is located in the sodium coolant channel at the core support plate elevation. The stainless steel lead cable wires are resistance welded to the outer wall of the tube making up the flowmeter inner cylinder wall. The lead cable exits the flowmeter through a braze sleeve and extends into the flow stream protected by an enclosing 3/16-in. diameter tube. The tube covers the lead cable until the cable enters the nonflow cavity in the bottom end plug of the tightener rod. Stress in the lead cable is minimized by a small amount (1/16 in.) of slack in this section of lead cable. The lead cable enters the tightener rod through a braze sleeve and follows the same course as the coolant thermocouples described in Paragraph 3.5.1.1.

3.5.3.2 Materials

The sheath material for the flowmeter lead cable was selected as Inconel ASTM SB-163. The wire conductor material was 0.0126-in. diameter ASTM-A-478 Type-304L stainless steel. The lead cable insulation was magnesia with a density of 85% to 88% of theoretical.

3.6 ELECTRICAL CONNECTORS

3.6.1 Description (Function)

The design and testing of the connector (see Figure 3-8) is described in Reference 2. The connector operates inside the reactor vessel, sealed from the sodium vapor, during reactor operation. During reactor shutdown, with the vessel head removed, for removal or insertion of an instrumented fuel assembly the connector would be open. During reactor operation the temperature may be as high as 1000°F. During reactor shutdown the temperature will be between 300°F and 400°F. The connector is capable of accommodating 20 leads from reactor core sensors.

The connector flange bolts are accessible from the top when the reactor vessel head is removed. The body of the connector is a precision fit into the flange and at the same time a lip for seal welding was provided. The interface points with other components can be seen in Figure 3-5. The flange containing the male connector was welded to the split, forged 180 degree return at the top of the assembly.

The female connector is contained in the vessel internal connector flange (Figure 3-8). This connector flange with a sealing cap (in place of the IFA) was installed in the reactor vessel prior to the reactor system sodium fill. Later during a reactor shutdown the sealing cap was removed and the connector made-up as an IFA was installed in the reactor.

Figure 3-8. Electrical Connector and Connector Flange

3.6.2 Materials

The material for body of the electrical connector was selected as Inconel alloy X-750. A ring of Type-347 stainless steel was electron-beam welded to the Inconel body providing a final lip seal weld between two pieces of 300-series stainless steel.

The pins and sockets were made from Inconel alloy X-750.

The ceramic inserts were WESGO AL300 (Western Gold and Platinum Company, Ceramics Division).

3.7 FLOWMETER MAGNETS

3.7.1 Description (Function)

Permanent magnets (Figure 2-6) were used in the flowmeters to provide the magnetic field to generate an electrical voltage signal as sodium flows perpendicular to the magnetic lines of force. The magnets in the shape of a ring were enclosed in a stainless steel container with a thin wall (0.020-in. thickness) on the magnet inside diameter. The sodium is excluded from the inside of the flowmeter. The lead wires are resistance-welded to the opposite sides of the inner cylinder in a separation space, with a ring magnet on each end. The lead wire junctions are 90 degrees from the north and south magnet poles.

The magnets were stabilized at 1000°F before fabrication of the flowmeters. Normal operation of the flowmeters in the reactor is at 720°F, core inlet temperature.

3.7.2 Materials

The cast Alnico 6 was circumferentially oriented. After the units were magnetized they were stabilized for 1000°F service.

3.8 CERAMICS

3.8.1 Beryllium Oxide

3.8.1.1 Description

The beryllium oxide insulators used in the fuel thermocouples are described in Paragraph 3.5.2.2.3. The second use of beryllium oxide was in the tightener rod where the material is used to soften the neutron spectrum of the core. Figure 3-9 shows the annular shaped beryllium oxide pellets in the trough holder prior to insertion in the tightener rod tube.

The moisture content of the tightener rod pellets was less than 16 ppm.

The total gas release from the pellets causes an increase in gas pressure of approximately 40 psi during reactor service. Clearance and spring loading of the pellet column accommodates the predicted maximum 2% length increase during the reactor service life.

3.8.2 Other Ceramics

Magnesia with a purity of greater than 99 wt % and a density of 85 to 88% of theoretical was used in all leadout cable. The thoria and alumina are described in Paragraph 3.5.2.2.3.

Figure 3-9. Tightener Rod Components (Beryllium Oxide Pellets in Trough Holder)

4. FABRICATION PROCESS DEVELOPMENT

4.1 GENERAL DISCUSSION

4.1.1 Discussion

The job required the manufacture of 24 fuel thermocouples for 6 instrumented fuel assemblies. In addition to these 24 thermocouples, 3 (one of each type) were fabricated for test purposes and 6 were remade due to fabrication losses prior to completion of the fuel rods.

4.1.2 Thermocouple Type

The assembled thermocouples by type:

- a. 0.140-in. diameter probe type (sheathed)
- b. 0.063-in. diameter probe type (sheathed)
- c. Bare wire probe type

4.1.3 Thermocouple Listings

The final listing of thermocouples made were:

IFA Number 1
(VNC 25)
197R243G5

4.1.2 (B)
4.1.2 (B)
4.1.2 (A)
4.1.2 (B)

IFA Number 2
(VNC 24)
197R243G6

4.1.2 (A)
4.1.2 (C)
4.1.2 (C)
4.1.2 (A)

IFA Number 3
(VNC 28)
197R243G4

4.1.2 (B)
4.1.2 (B)
4.1.2 (B)
4.1.2 (B)

IFA Number 4
(VNC 29)
197R243G1

4.1.2 (B)
4.1.3 (B)
4.1.2 (B)
4.1.2 (B)

IFA Number 5
(VNC 26)
197R243G3

4.1.2 (A)
4.1.2 (C)
4.1.2 (C)
4.1.2 (A)

IFA Number 6
(VNC 27)
197R243G2

4.1.2 (A)
4.1.2 (C)
4.1.2 (A)
4.1.2 (A)

4.1.4 Functional Requirements

The functional requirements of the fuel thermocouples were that they measure temperatures up to 4500°F in a nuclear environment while exposed to mixed plutonium/uranium oxide fuel. These thermocouples were required to (1) operate under steady-state and transient conditions from 800°F to 4500°F; (2) operate immersed up to three inches in a mixed plutonium/uranium oxide and fission gas environment of 500 psi (maximum) external pressure and atmospheric internal pressure (excluding gas expansion pressure in the high temperature probe sheath), with the exception of the bare-wire type of thermocouple.

4.1.5 Design Requirements

The hot junction of the sheathed design was electrically grounded to the sheath both by welding and mechanical means.

The hot junction of the sheathed thermocouple was seal-welded to the tungsten/rhenium alloy sheath. The seal weld was accomplished in an inert atmosphere at 1 atm pressure by seal-welding of the mechanical plug junction using a chill block on the remaining sheath, plug and wire assembly.

The hot junction of the bare wire thermocouple was formed by twisting four times the two tungsten/rhenium wires at their terminal point and fusion welding the wire ends together under an inert atmosphere.

The tungsten/rhenium alloy thermocouple wires were of two sizes: 0.010-in. diameter and 0.005-in. diameter (Number 30 and Number 36 B + S wire gauge, respectively). In the 0.140-in. diameter sheath type, the W/Re wires in the probe had a sine wave of nominal 0.018-in. height with approximately 4 waves per inch. The wave design section extended from the hot junction to the transition area. The 0.063-in. diameter sheath type had as much slack as possible between the hot junction and transition area.

The thermocouple wires were continuous, unspliced tungsten/rhenium alloys from the hot junction to the transition and were not subject to cold working or other processes resulting in deviation of the thermocouple calibration. The sheathed leadout contains Hoskins compensated thermocouple alloy 405 and 426 and were likewise not subjected to processes affecting the calibration results.

The resistance of the insulation between the two wires and each wire and sheath was greater than 500 megohms when tested at ambient temperature with an impressed voltage of 500 volts dc.

Dummy thermocouples were fabricated for the purpose of measuring reactor core noise which might affect thermocouple readings. The dummy thermocouples consisted of two legs of tungsten 26% rhenium alloy in the high temperature region and two legs of Ni20Cu alloy in the leadout wire. All dummy fuel thermocouples were of the 0.140-in. diameter type.

Bare wire thermocouples were fabricated to have a fast time response. They were fabricated from 0.010-in. diameter tungsten/rhenium wires and joined to the standard Hoskins Ni5Cu/Ni20Cu leadout wires at the transition.

The transition junction was made utilizing the spiral wrap concept. This concept employs a 1/16-in. X 1-in. long X 0.005-in. thick ASTM-B-160 nickel piece formed with a spiral insuring a 1/16-in. minimum gap between the jointed wires.

4.1.6 Specifications

The high temperature fuel thermocouples were fabricated per the following specifications.

Sheathed Lead Cable (1/8-in.) for Fuel Thermocouples—Number 22A1657.

Thermocouple Fabrication Process for SEFOR IFA's—Number 22A2332.

4.1.7 Materials of Construction

Nickel ribbon spiral wrap—1-in. X 0.032-in. X 0.005-in. thick ASTM-B-160 nickel.

Tungsten 5%/rhenium and tungsten 26%/rhenium thermocouple wire 0.010-in. $\pm$ 0.001-in. o.d. and 0.005-in. $\pm$ 0.0005-in. o.d.

Sheathed lead cable—15 foot long, Inconel sheathed, magnesium oxide insulation with Ni5Cu and Ni20Cu compensated lead wire.

Alumina (Al_2O_3) Insulators

Aluminum oxide transition insulators, double bore, 0.125-in. o.d. X 0.046-in. i.d. holes.

Alumina insulating tubing (single bore) 0.046-in. o.d. X 0.014-in. i.d. X 1/4-in. long.

Thoria (ThO_2) Insulators

Thorium dioxide insulators, double bore, 0.040-in. o.d. X 0.010-in. i.d.

Thoria insulators, double bore, 0.093-in. o.d. X 0.020-in. i.d.

Beryllia (BeO) Insulators

Beryllium oxide insulator, double bore, 0.040-in. o.d. X 0.010-in. i.d.

Beryllia insulation, double bore, 0.093-in. o.d. X 0.020-in. i.d.

Tungsten/rhenium sheath tubing

0.140-in. o.d. tungsten/26% rhenium by 21-inches, 6-inches, and 3-inches long.

0.063-in. o.d. tungsten/26% rhenium by 21-inches, 6-inches, and 3-inches long.

Thermocouple sheath transition tubes for 0.140-in. and 0.063-in. diameter tungsten/26% rhenium tubes—ASTM-B 166 Inconel-600 material.

Tungsten/26% rhenium end plugs—0.043-in. o.d. X 2 holes (0.005-in. i.d.) and 0.100-in. o.d. X 2 holes (0.010-in. i.d.); both 1/8-in. long.

Eutectic braze material, palladium 60%, nickel 40% (melting point 2260°F).

Pure copper oxygen free high conductivity (OFHC) braze material (melting point 1072°C).

4.1.8 Process Equipment Used in Thermocouple Fabrication

Lepel Power System—45 kVA maximum, Model T-20-30F. (See Figure 4-1.)

High Vacuum System—6 inch, Stainless Steel, 1×10^{-5} mm. (See Figure 4-2.)

Vertical Hydrogen Cleaning Furnace and Sanborn Recorder—Multiple Unit, Hevi-Duty Electric Company, Type M-5036. (See Figure 4-3.)

Vertical Hydrogen Brazing Furnace—IPO Designed and Built—No Catalog Number. (See Figure 4-4.)

Figure 4-1. 20KVA Power System

Figure 4-2. Vacuum System

Figure 4-3. Vertical Hydrogen Cleaning Furnace

Figure 4-4. Vertical Hydrogen Brazing Furnace

Helium Leak Detector—General Electric Mass Spectrometer Leak Detector, Type M-60, 2×10^{-8} torr.

Optical Pyrometer—Micro Optical Pyrometer, Type M5146, Range 700° to 3200° C.

Gas Purifier—Deoxo Puridryer, Engelhard Industries, Incorporated. (See Figure 4-5.)

Special Atmosphere Glove Box. (See Figure 4-6.)

Multiple Containment Vertical Hydrogen Furnace. (See Figure 4-7.)

Special Vacuum System Transgression Port. (See Figure 4-8.)

Resistance Measuring Device—Wheatstone Bridge Model RN-1, Industrial Instruments, Incorporated.

Multitest Device—Milliammeter, Millivoltmeter, Sensitive Research.

Megohm checker, Vibrotest Model 2850, Associated Research, Incorporated.

Radiographic Device—Industrial X-ray Unit, GE Model 11AD1/I, 175 kV, 12 Milliamp.

4.1.9 Special Jigs and Fixtures

A number of jigs and fixtures were designed and fabricated for this work effort.

All jigs and fixtures used to fabricate the thermocouples were identified by the pertinent blueprint number being vibra-etched on the fixtures main body portion. Along with the blueprint number, the part number was vibra-etched on the fixture body. The fixtures are referenced within the text of the report and are illustrated by the appropriate photographs.

4.1.10 Quality Assurance and Control

4.1.10.1 Quality Control Records

The following quality control records were maintained for each thermocouple:

Material certification papers including

- a. Material composition and heat numbers
- b. Mechanical properties
- c. The results of special tests such as radiography, dye penetrant, ultrasonics, etc.

Incoming Inspection Reports

The completed and initialed assembly sequence diagrams. This included:

- a. Leak checks
- b. Resistance readings of the thermocouple leadout cable and completed thermocouple
- c. Results of the x-rays and their reference numbers.

X-ray films and the recorded reference numbers.

Figure 4-5. Gas Purifier

Figure 4-6. Glove Box

Figure 4-7. Multiple Containment Vertical Hydrogen Furnace

Figure 4-8. Vacuum System Transgression Port

Thermal cycle/calibration results in the form of:

- a. Strip chart recordings
- b. Data sheet
- c. Converted emf's to temperatures-versus-standard results.

4.1.10.2 Quality Control Special Tests and Test Standards

The tungsten/rhenium thermoelement wire was tested for continuity and uniformity. This was accomplished by heating the wire to 1000°F. As the wire was passed through the heat zone, continuous monitoring was conducted by using a micro-voltmeter (see Figure 2-10). If a 50-microvolt emf was generated the defective portion of the wire was discarded.

A 10-to-30 power microscopic inspection of the tungsten/rhenium thermoelement wire was conducted. This was accomplished over the entire length of the wire. This inspection was used to locate and eliminate any portions of the wire containing nicks, gouges and/or fiber-separated areas.

The mass spectrometer leak checking devices were tested and calibrated per IPO Shop Procedure 22A2424. All leak checks were considered satisfactory if the indicated leak rate was less than 2×10^{-8} cc/sec. Leak checks were made as required on the assembly sequence diagram.

All completed thermocouples were calibrated for emf output at various set temperature levels. Two thermocouples were placed in the vacuum furnace, one fuel thermocouple and one standard thermocouple with the probe end positioned in a suitable heat sink, and a vacuum of 1×10^{-5} mm was developed after which the sensors were heated by a high frequency generator of 180 kilocycles. The thermocouple leadout wires were connected to a millivoltmeter and to a Sanborn recorder for emf readings. Five thermal cycles from 200°F to 1000°F were conducted with the thermocouple emf signals being monitored. The millivolt output readings for the first and fifth cycles were recorded. These readings were compared to the standard. If the deviation from the standard was greater than $\pm 1\%$ the thermocouple was rejected (see Figure 4-9).

It was necessary to phase or match the thermoelement and leadout wires so that they could be connected in the proper way. This was accomplished by connecting a millivolt meter to the top end of the thermoelements and applying a heat source to the other end of the thermocouple. The wires were phased so that there was a positive reading on the meter. The positive connecting wire was traced from the meter to the thermocouple and recorded. This was repeated on the thermocouple leadout wire, the four wires phased positive-to-positive and negative-to-negative.

4.1.11 Cleaning of Materials

The cleaning of materials used in the manufacture of high temperature thermocouples was critical for the long operating life of the sensors. Therefore, all materials were cleaned and fired in a controlled atmosphere.

All tungsten parts, i.e., tubing, wires and end plugs, were cleaned in a 20% solution of boiling potassium hydroxide (KOH) for five minutes followed by three rinses in water. These parts were then cleaned by firing at 1000°C for 30 minutes in a reducing gas (see Figure 4-10).

The firing (cleaning) of the tungsten wire was accomplished in a vertical glass tube furnace by passing hydrogen gas down over the wires while an electric current was applied to the tungsten wires. An optical pyrometer was focused on the wire giving visual control of the temperature (1000°C) at all times.

The small tungsten tubes, 0.064-in. diameter, required an additional step prior to the chemical cleaning. This was necessary because these small tubes had obstructions on the inside which would not permit the passing of the ceramic insulators through the tubes. To remove these obstructions a tungsten wire was used. The tungsten tube was placed over the twisted, pure tungsten wires and then moved along the wire with a reciprocating and turning motion while applying a mixture of water and very fine aluminum oxide powder.

Figure 4-9. Fuel Thermocouple Calibration

Figure 4-10. Firing (Cleaning) of Tungsten/Rhenium Wire

The Inconel transition sleeve was fired in a vacuum furnace at 1100°C for a period of 30 minutes while under a vacuum of 1×10^{-5} millimeters mercury. The material was allowed to cool under vacuum. This operation removed oxides prior to making a braze.

The Inconel-sheathed leadout wire (1/8-in. diameter X 15 feet) was cleaned in the braze region by dental alumina powder blasting. Both ends were opened and dental blasted. A megohm resistance reading was taken at this time. Upon completion of the recording of the resistance readings, one end was sealed with Glyptol while the wires protruded out of the seal. The open end was held under a vacuum or in a controlled atmosphere until the thermocouple was completed.

The nickel ribbon used for the spiral wrap was cleaned by acetone using ultrasonic means. The nickel was next placed in a hydrogen furnace and heated to 800°C for 15 minutes. The nickel was then ductile and oxide free. This operation was completed prior to forming the ribbon into a spiral wrap.

The beryllia insulators were cleaned by means of a vacuum furnace. These ceramics were placed in a molybdenum container. The unit was evacuated to a pressure of 1×10^{-5} mm and heated to 982°C for a period of 15 minutes. The power supply for this procedure was a high frequency generator. After firing, the beryllia insulators were kept in a desiccator.

The thoria insulators were fired in a hydrogen atmosphere at 1600°C for a period of two hours. The high firing of thoria required that the material be placed and supported in a molybdenum boat in such a manner that the thoria would not warp.

The alumina ceramics were used as received from the vendor.

4.1.12 Safety

Safety was of primary importance when manufacturing with the aide of hydrogen gas. The technician was well trained in the application of all related knowledge; methods, research and processes in the field of manufacturing and building devices incorporating hazardous material or procedures.

4.2 FUEL THERMOCOUPLE FABRICATION

4.2.1 Bare Wire

Two bare wire types of thermocouples were made, which differed in the length of the bare wire (unsheathed) probe portion. The short thermocouple had a bare wire length of some 7-1/2 inches with no tungsten support tube whereas the lone one was 5-5/8 inches long plus a 13-inch length of tungsten support tubing below the transition sleeve area.

The first step in fabrication involved the cleaning of parts as described previously. A Type-304 stainless steel insert was tack-welded into the bottom end of the transition sleeve. This insert had a small ridge on the bottom end of the inside diameter which prevented the thoria insulator from sliding out.

Preliminary work included making the spiral in the nickel foil. The ductile nickel ribbon was wrapped on a mandrel of 0.020-in. diameter. The mandrel was partly removed and the nickel trimmed square. A small mandrel (0.010-in. diameter) was then inserted in the open end and the nickel ribbon was reformed to fit this smaller diameter mandrel. The large mandrel was withdrawn completely and the other end of the nickel trimmed square. The result was a spiral-wrap transition piece with expansion joint characteristics. Two of these spiral-wrap pieces were needed for each thermocouple (see Figure 2-13).

4.2.1.1 Upper Thermocouples

A pair of wires 0.010-in. in diameter, one of the tungsten/5% rhenium and the other of tungsten/26% rhenium were selected. A check was then conducted to assure that billet numbers and certification papers were complete. This information was entered on the assembly sequence diagram. Next, the 0.075-in. o.d. single-bore alumina insulators were

strung on the wires. The wires were held in place on a fixture as shown in Figure 4-11. The tungsten wire was cut approximately 4 inches longer than required for the finished thermocouple. For one thermocouple 50 insulator beads per wire were used and on the second thermocouple only 26 beads are used per wire.

After the small beads were in place, the Inconel transition sleeve slid over the lower end of the two wires and was secured in place on the fixture. Next, the thoria insert (double-bore insulator) for the transition junction slid over the two wires from the top end. This was followed by the double-bore alumina transition insulator (0.124-in. o.d.). The alumina insulator was allowed to protrude out the top of the Inconel transition sleeve before it was clamped in place.

Next, the nickel spiral wraps were placed on the thermoelements and crimped lightly. The wire out of the alumina-ceramics top end was adjusted to a convenient length (see Figure 4-11). With the upper end of the insulator beads held in place, the double-hole thoria probe ceramic slid over the lower end of the two thermoelements. The thoria was brought into contact with the lava fixture spacer and clamped in place.

The copper chill block was positioned over the wires and tightened in place. The thermocouple was now ready for attachment to the 1/8-in. Inconel-sheathed leadout wires.

With the leadout wire mounted in the four-inch hydrogen furnace, the phasing of the leadout wires was checked and logged. The phasing of the wires on the thermocouple mounted in the holding fixture was checked.

The thermocouple holding fixture (see Figure 4-11) was placed on the 1/4-in. round vertical rod in the hydrogen furnace ensuring that the wires were properly matched. The capscrews holding the copper chill block were loosened and the thermoelements moved so the nickel spiral wraps slid over the Ni5Cu and Ni20Cu alloy wires extending from the sheathed Inconel leadout wire.

Using a molybdenum filament 0.005-in. thick and 3/16-in. wide, one nickel spiral-wrap thermoelement was placed in position at a time, and with the braze material in place the system was purged. Then the braze was made in the reducing atmosphere. The spiral-wrap leadout wire brazes were made in the same manner. The braze material used at the Ni5Cu and Ni20Cu wires-to-nickel spiral-wrap was nickel 40%, palladium 60%, and for the tungsten/rhenium-to-spiral-wrap OFHC copper was used. This operation is shown in Figure 2-13. During this operation, the power to generate the heat was applied until the braze material was observed to be melting (flowing). At this point the power was shutoff.

After completion of all four brazes, the holding cap screws were loosened on the back of the thermocouple fixture (Figure 4-12). The fixture was carefully lifted, passing over the brazes. The alumina insulator clamp was removed and the Inconel transition sleeve was moved to a position 5/16-in. above the end of the leadout wire. The holding fixture was clamped again to the 1/4-in. vertical rod. Adjustments were made and the final braze (using OFHC copper) was made between the Inconel sheath and the Inconel transition sleeve. This braze was made in a hydrogen atmosphere. Upon completion, the entire unit was removed from the hydrogen furnace and placed in the holding tube.

The bare wire thermoelements were twisted four times and then cut to length. The entire unit was next inserted in a controlled atmosphere and pumped down to a pressure of five microns, then back-filled with dry helium gas (repeated four times). The hot junction or probe tip was then welded.

Upon completion of the thermocouple fabrication, it was removed from the controlled atmosphere. A continuity and a resistance check was made leg-to-leg and legs-to-sheath.

These values were recorded on the assembly sequence diagram. To protect the bare wire section, a long thin stainless steel tube was placed over it. One end of this tube was flared to fit over the transition sleeve and thereby hold it in place. This protective tube remained in place at all times except during certain tests such as x-ray and thermal cycle (calibration). The transition sleeve-to-leadout sheath braze was leak-checked. After this the thermocouple was calibrated in a vacuum furnace (see Figure 4-13). One or more sensors were mounted in a heat sink with a calibrated standard thermocouple as a control sensor. The vacuum system was pumped down to 1×10^{-5} mm before the high frequency power was applied. A millivoltmeter was attached to the leads of each thermocouple. Power was slowly

Figure 4-11. Thermocouple Fixture

Figure 4-12. Thermocouple Brazing Fixture

Figure 4-13. Thermocouple Furnace Fixture

applied to the heat sink until the proper emf was obtained from the standard thermocouple. The temperature of 1150°C was maintained for 30 minutes, at the end of which the power was gradually decreased to zero. During this time the output emf was observed at all times for incongruities.

Again a continuity check was made. The thermal cycling and calibration process was conducted as previously stated. After this the thermocouple was x-rayed and the x-ray identification number recorded on the assembly sequence diagram. A final continuity check was conducted just prior to putting the thermocouple in storage. The bare wire thermocouple was put in a specially sealed container. This container was back-filled with helium to provide a controlled atmosphere (see Figure 4-14).

When a thermocouple was completed, the quality control folder containing the assembly sequence diagram, thermal cycling data sheet and recording strip charts and x-rays were forwarded to the Manufacturing Project Engineer. This folder was then placed in the appropriate IFA folder which also contained all of the material certification papers for the materials used in the fabrication of the thermocouples.

4.2.1.2 Bare Wire Thermocouple for Peak Flux Position

(See Figure 4-15.) This thermocouple was fabricated in an identical manner as was the lower flux position type with the following listed minor changes.

A 13-7/32-in. tungsten tube was brazed into the transition sleeve as the thermocouple sheathing. The end of this tungsten tubing was so formed as to have a small lip rolled inward at the bottom end. This acted as a retainer for the thoria insulator so that it could not slide out of the tube. The last thoria insulator in the bottom of this sheathing was ground down to a diameter of 0.082-in. for a length of 3/32-in., to prevent shorting of wires to the sheath.

The braze of the Inconel transition tube to tungsten sheathing was the first step in making the peak flux position bare wire thermocouple. This braze was made in the vacuum furnace held in place in a weld fixture. See Figure 4-16. The braze material was 40% nickel, 60% palladium and was held at power 30 to 45 seconds after the braze-material flow was first observed. After the braze was completed, it was leak-checked and results were recorded on the assembly sequence diagram.

The only other difference between the two bare wire thermocouples was that 26 alumina insulator beads per thermoelement were required on the peak flux thermocouple instead of 50 on the 75% average flux thermocouple. All other fabrication steps were followed as previously described in Section 4.2.1.1.

4.2.2 Small Diameter Fuel Thermocouples

The small diameter, sheathed fuel thermocouple was made in three variations. The one thermocouple (75% average flux position) had a straight 4-3/16-in. probe length below the transition sleeve while utilizing beryllia insulation. The other two thermocouples (peak flux position) had an offset and a 17-17/32-in. probe length below the transition sleeve. The only difference between the peak flux position thermocouples was that one used beryllia insulators and the other used thoria insulators. The thermoelement wires were 0.005-in. in the small-diameter thermocouples versus 0.010-in. diameter in the large-diameter thermocouples.

The preliminary assembly steps of cleaning, firing and preparing the nickel spiral wrap wire were the same as for the bare wire thermocouple process.

The first step in fabricating the 75% average flux thermocouple was to braze the tungsten probe sheath tube to the Inconel 600 transition sleeve. This was done in a fixture while under a hydrogen atmosphere using the 40% nickel, 60% palladium brazing alloy. Again the power was allowed to remain on for 30 to 45 seconds after the brazing alloy material was observed to flow. After this braze, the brazed joint was leak-checked and so recorded on the assembly sequence diagram.

The two thermoelement wires 0.005-in. diameter tungsten/26% rhenium and tungsten/5% rhenium wires were placed in the wire holding fixture. Threaded over the bottom ends of the two thermoelements were double bore 0.042-in. o.d. beryllia insulator beads for the required length. The beads were of random lengths and first placed in a

Figure 4-14. Sealed Container

Figure 4-15. Bare Wire Thermocouple

Figure 4-16. Sheath Transition Brazing Fixture

tray to obtain the correct overall length. The tungsten probe-transition sleeve subassembly was threaded into position from the bottom end over the beryllia insulators. Next the double bore alumina ceramic was threaded into place from the top end over both wires. The entire thermocouple subassembly was then clamped into place as shown in Figure 4-17. The two previously prepared nickel spiral wrap connectors were put in place and lightly crimped to the tungsten wire. The leadout wires and the thermoelement wires were phased and joined positive-to-positive and negative-to-negative. Using the 0.005-in. thick molybdenum heater element strips, the Ni5Cu and Ni20Cu leadout wires to spiral wrap brazes were made using nickel 40%, palladium 60% brazing alloy. The spiral wrap-to-tungsten/rhenium wire brazes using OFHC copper were made next. All four of these brazes were made in a reducing atmosphere of dry hydrogen. Before any additional work was done, a continuity check was made.

The final braze made in the hydrogen furnace was the transition sleeve-to-the Inconel wire leadout sheath. This was done after the transition sleeve was threaded up over the spiral wrap brazes and clamped into position. This braze was made using OFHC copper as previously described. Upon completion, another continuity check was made and recorded.

The tungsten end plug was threaded over the thermoelement wires and inserted into the tungsten probe sheath. This subassembly was then mounted in the probe welding fixture. The entire unit was mounted in the inert gas welding chamber. The chamber was pumped down for a period of four hours to a pressure of five microns, back-filled three times with a dry helium gas before proceeding. The following two welds were made using a copper chill block surrounding the probe sheath. First the end plug was welded to the tungsten probe tube and then the thermoelements were welded to the end plug.

Upon completion of the thermocouple fabrication it was removed from the controlled atmosphere. A leg-to-leg continuity check was made as was a resistance check of leg-to-leg and each leg-to-sheath. The lower portion of the thermocouple including the transition sleeve was then tested for integrity on a mass spectrometer leak detector with leakage limit not exceeding 2×10^{-8} cc/sec helium.

One or more sensors were mounted in a heat sink with a calibrated standard thermocouple as a control sensor. The vacuum system was pumped down to 1×10^{-5} mm before the high-frequency power was applied. A millivoltmeter was attached to the output leads of each thermocouple. Power was slowly applied to the heat sink until the proper emf was obtained on the instrumentation. The temperature of 1000°F was maintained for 30 minutes, at the end of which time the power was gradually decreased to zero. During the temperature holding process, the output emf was observed at all times for any sudden changes indicating incongruities.

Again a continuity check was made. The thermal cycling and calibration process was conducted as previously stated. After this the thermocouple was x-rayed and the x-ray identification number recorded on the assembly sequence diagram. A final continuity check was conducted just prior to putting the thermocouple in storage.

When a thermocouple was completed, the quality control folder was forwarded to the Manufacturing Project Engineer. This folder was then placed in the appropriate IFA folder.

The fabrication of the peak flux position thermocouples was identical to the process just explained for the 75% average flux position thermocouple with the following exceptions. The first difference was in the substitution of the thorium insulating material for the beryllia in the probe.

The second difference entailed the need for forming bends in the probe. This was done to allow the thermocouple hot junction to be on the center line of the fuel rod. After the spiral wrap and transition-to-leadout wire brazes were made, the tungsten end plug was put in place. This partially completed thermocouple was then placed in the bending fixture. This is shown in Figure 4-18. The clamp holding the transition sleeve in place was secured next. The first bend was put in near the transition sleeve. Stops are provided so just the right amount of bending was performed. The first part of the lower end bend was put in as shown in Figure 4-19. In Figure 4-20 the last part of the bend has been made and the finished probe end is shown with the forming handle removed.

All other process steps and procedures were followed as previously described.

Figure 4-17. Small Diameter Thermocouple Fixture

Figure 4-18. Small Diameter Thermocouple Bending Fixture

Figure 4-19. Thermocouple Bending Operation Step One

Figure 4-20. Thermocouple Bending Operation Step two

4.2.3 Large Diameter Sheathed Fuel Thermocouples

The fabrication of 0.140-in. diameter series thermocouples were for all practical purposes identical to the 0.064-in. diameter series thermocouples.

The thermoelement wire diameter was 0.010-in. for the 0.140-in. diameter thermocouples. The respective lengths of the two thermocouples were the same as the insulating material; i.e., beryllia and thoria.

One additional preliminary step in fabricating the large diameter thermocouples was the forming of a sine wave in both thermoelement wires. This was accomplished by successive forming of the tungsten/rhenium wires in a roll-press fixture (sine wave). This is shown in Figure 4-21. One thermoelement wire at a time was inserted into the fixture. The top of the die was pressed down using only normal hand pressure. The wire was advanced and the process repeated until the entire length of the thermoelement wire was formed with the sine wave.

4.2.4 Thermocouple Fabrication Problems

Several problem areas existed continually throughout the fabrication of all thermocouples.

In general the tungsten/rhenium wire was a problem due to the lack of ductility. More specifically the tungsten/5% rhenium wire was found to be brittle. It was found that if a kink or relatively sharp bend was put in the W/5%Rh wire and if it did not break immediately, the wire would break in a matter of days without additional bending. Another characteristic of the tungsten/rhenium wire was a large number of flaws.

The tungsten tubing used as probe sheathing had two areas of concern and special consideration. There were obstructions on the interior of the tubing which required hand-honing to ensure the easy passage of the ceramic insulator beads. This process was previously described but it is worth mentioning that if the inside diameter is not properly and adequately honed out, the thermocouple can be lost in fabrication after a significant amount of contributed value has been added. Another problem associated with the tungsten tubing was that it would split longitudinally during the probe-forming operation. It was found to be advantageous to microscopically examine the outside diameter in the bend areas. After determining and plotting the location of the defects (ultrasonically) the tube was oriented in such a manner as to minimize the chances of fracturing the tubes.

The ceramic insulator beads were the cause of two problems. The first was due to the weakness in the bead walls and webs (minimum thickness to have larger holes). This caused breaks in those areas which allowed the thermoelements to short-out or become grounded to the sheath. The ceramic insulator beads were warped in some cases along the longitudinal axis thereby not passing freely through the tungsten tubes.

4.2.5 Thermocouple Weldment Fabrication

The fabrication of the thermocouple weldments involved the brazing of two appropriate thermocouples into the fuel element bulkhead. After this was completed, a bulkhead braze protective cap or guard was brazed into place. The weldments differed to the extent that different thermocouples were used and their physical configuration and hot junction locations varied.

The fabrication of all weldments was essentially identical and therefore only one type is described in detail. The only significant difference, that of using a bare wire thermocouple, will be explained showing these differences. The following description is of the assembly of weldment incorporating two 0.064-in. diameter sheathed thermocouples.

A special fixture was required for each different weldment. The fixture for weldment was constructed so as to hold the sensors in their proper relationship to each other. The fixture itself (see Figure 4-22) consisted of a steel bar 1/4-in. thick, 2-in. wide, and 26-in. long. This fixture had a cylinder type base, so that it fit and centered into the 6-in. vacuum system. Along the flat of the fixture were located the thermocouple tungsten probe holding bars which were removed by the withdrawal of the two screws in each bar. In the area near the top of the fixture there were three holding clamps. These clamps held the thermocouples in proper relationship to each other and applied pressure on the Inconel transition sleeve. Directly above this area, the leadout wire had offset bends. The offset was accomplished after the thermocouples were placed on the fixture, held in proper relationship and bent around fixed pins. For further

Figure 4-21

Thermoelement Sine Wave Forming

Figure 4-22. Thermocouple Weldment Fixture

details of this forming operation, refer to the thermocouple fabrication section of this report. Immediately below the holding clamps was a centering ring which was installed on the bar and used to center the fixture in the Vicor glass.

From the top end of the lead wires, the spacer was slid on. This was followed by the guard, Part 6 of GE Drawing 135B9231. Both parts slid down the two wires until they were within approximately four inches of the top of the thermocouple weldment fixture. The guard was then tied off with a small diameter stainless steel wire to prevent its sliding down further. The spacer was forced down the two leadout wires until it made physical contact with the lower part of the molybdenum heat sink. This was adjusted so that the spacer seated uniformly on the heat sink surface. The molybdenum heat sink shield was slid down over the wires until it also seated on the heat sink. The multifeed-through-vacuum head, Figure 4-8, was installed over the leadout wires. Each feed-through port had a special fitting and demanded the utmost attention by the technician so as not to damage the "O" rings. When the multifeed-through-vacuum head was in position, the piece of Vicor glass tubing was carefully brought up into place from the bottom end of the thermocouple weldment fixture. It was engaged in the multifeed-through head by tightening the cap screws on the head. This formed a vacuum-tight seal. The glass, head, weldment, thermocouples and fixture were now handled as a single unit.

This unit was then brought to the high vacuum station and installed. See Figure 4-1. The base of the weldment was engaged with the vacuum system. This assisted the fixture to remain in the vertical position while the Vicor glass was slid into position over the weldment and through the high frequency generator work coil. The Microbrazing Number 30 material was applied to the joint and the wire clamps were secured. The leadout wire was secured to the leadout wire holding fixture and mounted over the upper end of the high vacuum system. After the vacuum seals were tightened and properly adjusted, the system was pumped down to 1×10^{-5} mm for several hours. At the end of this period of time, the power was applied to the high frequency generator work coil and the braze completed using an optical pyrometer for temperature control. Both brazes were made simultaneously. The completed braze was completely cooled before the vacuum system was opened.

With the system open, the Vicor glass was raised high enough to completely expose the molybdenum heat shield. The restraining wire was removed from the guard and the guard lowered down inside the spacer. The guard was made to contact the spacer. A ring of braze material was placed around the guard and in contact with the spacer. The brazing alloy used was 5% palladium, 95% silver. The system was closed and pumped down to approximately 1×10^{-5} mm for several hours. The power was applied slowly from the high frequency generator while observing the condition of the vacuum system. It was necessary to continually check the condition of the braze material while power was being increased. The optical pyrometer was used for temperature control of the braze.

Upon completion of the final braze, the weldment was removed from the vacuum system as a unit. The fixture and weldment were separated. The weldment was placed in the transfer case. See Figure 4-14. The transfer case was placed in the mass spectrometer leak detector and a check of the weldment braze was made. Upon successful completion of this test, the transfer case was removed from the leak detector and the open end was closed with the seal plug. The weldment was now completed and ready for shipment.

Assembly of the bare wire thermocouple weldment was the same as the description of the preceding weldment except that the bare wire thermocouple transition sleeve was so located that it was subject to an excessive amount of heat. This was due to the close proximity of the molybdenum heat sink to the transition sleeve during the braze period. A special weldment fixture was constructed for this braze which was water-cooled. A water line through the lower part of the six-inch tee in the vacuum system circulated water around the transition sleeve. This used a copper chill block. This fixture is shown in Figure 4-23.

The bare wire thermocouple required that they (the thermocouples) be placed in a glove box and pumped down to a vacuum of 5 microns, back-filled three times with dry inert gas, and the carrying case sealed in the glove box without exposing the bare wire thermocouples to the atmosphere.

As a weldment was completed, with the quality control checked and the data package completed, it was delivered to the Plutonium Laboratory where the weldments were stored in the carrying cases until needed for fuel rod fabrication.

Figure 4-23. Chill Block Fixture

There was relatively no development work required in combining the thermocouples into a weldment. The only area of concern was of establishing the proper brazing alloy. This was necessary to ensure a full penetration spacer braze which was leak tight. The other concern was to determine the best low temperature brazing alloy to use on the guard braze so as not to remelt the thermocouple-spacer braze. This was accomplished using the brazing alloy materials specified earlier.

Several problems occurred during the assembly of the weldments. The most prevalent problem was due to the frailty of the bare wire thermocouples. Several bare wire thermocouples were lost during this operation and had to be remade.

During one weldment brazing operation, oxidation was observed in the Vicor glass vacuum chamber. After an investigation it was found that a minute hole had developed in the water-cooled chill block. All parts had to be refired in a hydrogen atmosphere to remove the oxidation. Thermocouples and the spacer were salvaged and the braze remade after the repair to the chill block.

4.2.6 Thermocouple Development

The major areas in the fuel thermocouples development were: 1) probe end plug types, 2) brazing the transition area, 3) sine wave W/Re probe wire and 4) bending of W/Re sheathing.

4.2.6.1 Probe End Plug

Three different types of thermocouple end plug construction were possible as shown in GE Drawings 886D255 and 886D599. A development program was initiated to determine which end plug type was best for this application. Type I had never been used and as a consequence its design had to be shop tested before its design could be used for the thermocouple. There were questions on Type II and Type III methods being patent infringements and this was investigated. It was found that Type III method would be in conflict with Aero Research Company's patent and Type II was questionable from a patent view point. Type II initially seemed to be better primarily because of the familiarity with this design, ease of attaining end plug closure and the hot junction, and the belief that a mechanical wedging occurred with this design. However, this type had never been demonstrated using tungsten and tungsten/rhenium materials and with the flat-sided end plug wedging the wires against the probe i.d. This truncated plug was designed mainly to minimize excessive wire vibrations and provide a satisfactory hot junction. But when compared to the Type I design this became a disadvantage since the Type I wires are normally set in a straight relaxed position instead of with an offset causing induced bending stresses which resulted in wire failure.

The first tests were conducted to determine the optimum end plug length when fused to a W/Re tube and W/Re wires. Pure tungsten end plugs were machined at 3/32-in., 1/8-in. and 5/32-in. lengths. A chill block made from copper was used on one set of sample parts, while none was used for the others. After welding the W/Re wires were pulled and then relaxed using a spring scale until failure of the 0.010-in. diameter wire. All the welding was done in a recirculating helium atmosphere glove box. The W/Re tubes were 0.140 o.d. X 0.020-in. wall and cut in random lengths approximately 3/4-in. long. Results of the test are shown in Table 4-1.

Table 4-1
PULL TEST (TYPE II THERMOCOUPLE)

0.010-inch diameter wire and 0.140-inch diameter sheath

	26% Leg (lb)	5% Leg (lb)
No Chill Block		
3/32-inch end plug	2	0
1/8-inch end plug	9	16
5/32-inch end plug	1	14
Chill Block		
3/32-inch end plug	5	15
1/8-inch end plug	1/2	18
5/32-inch end plug	9	15-1/4

Results of photomicrographs showed a finer structure for the 26% Re than the 5% Re wire. The comparatively greater fracture strength in the 5% Re was due to the longitudinal split or seam inherent in the 25% Re wire. The end plug length does not appear to have any effect on the W/Re wire fracture strength.

The chill block end plug fusions required more heat for a longer time than the nonchill block. Balling-up of the chilled tube ends was not as apparent as for the nonchill block tube.

Investigations into fabrication of a swaged Type I thermocouple end plug design were then performed. It had been hoped to swage the end plug around the W/Re thermoelectric wires thus providing a hot junction away from the fused wire ends. Attempts were made both at room temperature and at 1000°F and neither yielded satisfactory results. The problems occurred in the swaging of the tungsten/rhenium tubing—0.140-in. diameter X 0.020-in. wall—to the tungsten end plug.

Type I end plug without the swaging was tried. All parts were fired in hydrogen for cleaning and the end plug and wires were fusion welded in a helium atmosphere. After fabrication, the end plug assembly was annealed to 1150°C in hydrogen. Pull tests were then performed and the data are shown in Table 4-2. Two wires sizes were tried, 0.140-in. o.d. sheath and 0.010-in. and 0.005-in. diameter wires.

Table 4-2
PULL TEST (TYPE II THERMOCOUPLE)

0.010-inch diameter W/26 Re Wire and 0.140-inch diameter Sheath

T/C No.	Wire No. 1 (lb)	Wire No. 2 (lb)
1	12-1/2	11
2	20	0
3	13	7
4	14	7

Pull Test (Type I Thermocouple) (without swaging)

0.010-inch diameter W/26 Re Wire and 0.140-inch diameter Sheath

T/C No.	Wire No. 1 (lb)	Wire No. 2 (lb)
1	13	0
2	15-1/2	7-1/2
3	16	7

0.005-inch diameter W/26 Re and 0.063-inch diameter Sheath

T/C No.	Wire No. 1 (lb)	Wire No. 2 (lb)
1	4	4
2	4	4
3	4-1/2	4

Type I and Type II data are very similar; however, Type I has the better design. Type II requiring the W/Re wires to bend from the plug center to the o.d. will affect thermocouple stability at high temperatures. Additional stresses are induced through vibration at the Type II plug and from the probe insulators. Type I is designed to allow the W/Re wires to protrude straight into the drilled end plug and this eliminates these stresses. Photomicrographs showed that the Type I design provides more support for the wires. This development program showed that the Type I construction will provide a more reliable and better thermocouple junction.

4.2.6.2 Thermocouple Transition Brazing

In the transition region where the leadout wire made from Ni5Cu and Ni20Cu is joined to the tungsten/rhenium probe wire. There are four brazing locations at this transition region; 1) nickel ribbon to the 0.020-in. Ni5Cu and Ni20Cu leadout wire, 2) nickel ribbon to 0.005-in. diameter W/5Re and W/26Re probe wires, 3) Inconel tube to W26/Re sheath and 4) Inconel transition tube to 1/8-in. diameter Inconel leadout sheath. Locations 1 and 2 are shown in Figure 2-13.

4.2.6.2.1 Nickel Ribbon to Ni5Cu and Ni20Cu Leadout Wire

Brazing of the nickel ribbon to the leadout wire was initially tried using pure copper.

Hoskins Number 405 composition is 95% Ni and 5% Cu.

Hoskins Number 426 composition is 80% Ni and 20% Cu.

The Hoskins alloy wire melted off and it was found after testing that alloying was occurring between the Hoskins alloy Number 426 and the nickel ribbon. This alloying lowered the Hoskins alloy Number 426 wire melting point and caused it to melt.

Pure silver was then used on all four wires simultaneously, to eliminate the possibility of over alloying, while in addition the neutron environment problem was checked. An unsatisfactory braze resulted.

Nicrobrazo Number 10, Number 30, and Number 50 were tried but the wire overalloyed and melted off at 1110°-1120°C. For Nicrobrazo Number 30, this seemed to be caused by alloying from the silver.

A palladium/nickel alloy was tried on the Ni20Cu wire to the nickel sleeve. The braze flowed well but due to the large amount of brazing material it eroded approximately 1/3 of the wire diameter above the braze. Next some Pd(60%)-Ni(40%) powder was obtained. This braze worked when a small amount of this material was used. The wire was heated to the braze melting point and held, thus this was accepted as a satisfactory braze.

4.2.6.2.2 Nickel Ribbon to W/5Re and W/26Re Probe Wires

Development work had begun on finding the proper brazing materials and techniques at the nickel ribbon-to-probe wire interface when it was found that a "doping" problem with the W/Re probe wires might exist. A report on the FCR-TREAT experiments showed that a W/Re thermocouple wire was affected by a doping agent which was promoting the wire breakage and creating porosity in the wire at high temperatures. Tests were run on the exact IFA fuel thermocouple materials and it was found that this problem did not exist either for doped or undoped W/5Re wire like that observed in the FCR-TREAT experiments. The gross porosity was then related to a molten Be O/W reaction (BeO being used as insulation material which melts as 4600°F) rather than to the doping agent.

Work continued on this braze; pure silver was used which produced poor results, poor flow and no fillet. A Pd/Ni braze was attempted but a brittle joint on the W/26Re wire occurred and broke the wire. The brittleness occurring in W/Re wire was found to be the result of leaching to the Re into the nickel. Copper was used at this nickel ribbon-to-W/Re wire joint and the braze looked good except the W/5Re wire broke several times at the stop-off. After this stop-off was eliminated and the alumina insulation moved away from the heat zone, satisfactory brazes resulted.

4.2.6.2.3 Inconel Transition Tube-To-W/26Re Sheath

Palladium/cobalt and palladium/nickel brazing materials were initially used; laboratory pull-joint tests and traverse hardness checks were performed to determine the brittleness and best brazing material. Palladium/nickel produced better braze results and was therefore selected.

4.2.6.2.4 Inconel Transition Tube To 1/8-In. Diameter Inconel Sheath

Palladium/nickel was selected for this joint but since the wire brazes inside the transition tube would melt due to the high temperatures, a chill block had to be used. With the chill block required to be located close to the braze area and the susceptor, the temperatures could not be evenly maintained to perform a satisfactory braze. OFHC copper was tried and it produced a very good braze.

4.2.6.3 Sine Wave in Probe Lead

A sine wave in the W/Re wires was required for temperature expansion in the thermocouple. In forming the first 0.010-in. diameter W/5Re wire to produce the sine wave, the wire broke. Metallography inspection showed radial cracks in the wire. These cracks are not unusual for this type of wire and when there are large enough cracks, or the wire is positioned just right during forming, it will break during the sine wave forming process. It was then required that the W/Re wire be pull-tested before the vendor shipped the wire. This election of wire batches improved the handling and forming of the W/Re wire.

4.2.6.4 Bending of W/26Re Sheath Tubing

Investigation into the feasibility of forming W/26Re tubing produced the following information from Hoskins Manufacturing Company. Forming W/26Re tubing is a delicate operation and certain conditions should be followed. Bending of a 1/16-in. o.d. X 0.010-in. wall tubing around a 3/4-in. bar is within the formability range of this alloy. It is preferable to heat (warm) the tube for optimum success but bending can be performed at room temperature using a forming mandrel.

The ductility of tungsten base alloys is better in a stress-relieved condition than in the recrystallized condition. The IFA Specification called for a uniform equiaxed grain size of ASTM Number 5-7. In order to comply with this, heat treating must be done at a temperature higher than that which should be used for optimum ductility.

During the development phase, bending of the W/Re tube was accomplished using a 0.125-in. o.d. X 0.015-in. wall X 10-in. long tube; 0.010-in. diameter W/5Re and W/26 wires were used with 0.062-in. aluminum insulators. A standard end plug was used for forming the thermocouple hot junction. A torr seal was used for sealing the cold end of the tube and for holding the two W/Re wires firmly in place during the bending. Fusion-welding the end plug was done in a recirculating helium glove box.

A simple bending setup was used. The tubing was held in the blocks and the bends were formed free-hand while an acetylene-rich torch was held at the bend area. A butane flame was used to heat the end plug region to prevent any brittle fracture of the W/Re wires during bending.

At the bend the oxygen-acetylene torch was used until the tube turned a straw color, then the tubing was worked to form the offset. An emery cloth was used to clean the oxidation on the tubing. Dye penetrant checks and a helium check were performed after bending; results were negative. Dimensional checks of the tubing showed approximately 0.0005-in. to 0.001-in. flaring at the ends which was acceptable.

During forming of this offset in the W/26Re sheathing for the first thermocouple fabrication the tube split at the bend area. In order to prevent this from occurring, a roller was made for bending. This worked satisfactorily and splitting of the tube was eliminated.

4.3 HIGH NICKEL BRAZE JOINTS

4.3.1 General Discussion

Several areas requiring the bonding together of two parts were made using a high-nickel brazing alloy. All of these brazes were made using either Microbraz Number 30 or Number 50. Although Microbraz Number 30 had a higher melting point, its advantage lay in its ability to bridge a gap of 2 to 4 mils. Microbraz Number 50, on the other hand, would not bridge a gap any greater than 1 mil.

There were seven major areas requiring the use of Microbraz alloying material. They were:

1. Seal Block Brazes, Figure 5-2 Part 21
2. Thermocouple Leadout Cables, Figure 5-2 Part 4
3. Thermocouple Leadout Cables, Figure 5-2 Part 20
4. Thermocouple-to-Lower Tightener Rod Lower End Plug, Figure 5-2 Part 23
5. Two Thermocouples-to-Tightener Rod Top End Plug, Figure 5-2 Part 22
6. Lower Tightener Rod End Plug-to-Pass Through Tube, Figure 5-2 Part 24
7. Flowmeter Leadout Cable-to-Pass Through Tube, Figure 5-2 Part 24

There were several additional brazes made using Microbraz, but these were made using a hand acetylene torch. These were noncritical brazes and will not be discussed separately. They are discussed in the main text of the assembly report.

The pressure vessel-to-thermocouple lead cable braze (Figure 5-2, Part 4) is discussed in detail in the Subassembly Fabrication Section, 5.3, Pressure Vessel Section. The Figure 5-2, Part 20-to-thermocouple leadout cables braze is identical to the Part 4 braze. Therefore, the only high-nickel brazes discussed in detail are Areas 1, 4, 6 and 7 above. The brazes required for Area 5 above were identical to Area 4, so they will not be discussed separately.

All brazes were made in conformance to GE Specification 22A1651, or its intent. Any changes to the specification required in fabrication had Engineering approval and these were documented by letter. Each braze process and technician were qualified by test. Qualification required repeatably making satisfactory braze samples. These samples were sectioned and tested to assure 1/8-in. braze alloy penetration, no porosity, helium leak tight, free of oxidation, and a minimum of parent metal grain growth.

4.3.2 Seal Block Brazes

The seal block brazes were made as shown on Figure 2-12. The first preparatory step was to TIG-weld (Tungsten Inert Gas) the stainless steel pass-through sleeves into the seal block. Dependent on the IFA group number, eight or nine pass-through sleeves were welded into place from the bottom side. Each weld was then leak-checked on the helium mass spectrometer. After successful completion of this test, the entire seal block was fired in a reducing atmosphere (hydrogen) at 1000°C for 30 minutes. At the appropriate assembly sequence time, the seal block was welded to the lower section of the IFA. This was done after all thermocouple leadout wires were threaded through the pass-through sleeves. The entire lower portion of the IFA was inserted into the specially designed and fabricated hydrogen furnace tank (see Figure 4-24).

The cover of the furnace was secured in place and the entire unit evacuated. This was accomplished by the use of a vacuum roughing pump connected to either end of the furnace chamber. The furnace was evacuated three times with intervening purges of helium ensuring a totally sealed chamber as well as no out-gassing of the IFA unit.

Figure 4.24. Hydrogen Furnace Tank

The furnace cover was then removed and the brazing alloy (Nicrobraz Number 30) paste was placed around one thermocouple leadout wire-to-pass-through sleeve junction. The 0.005-in. thick X 0.375-in. wide molybdenum heating elements were placed into position around the junction (see Figure 2-12). The furnace was closed, evacuated, purged with helium and evacuated again. Dry hydrogen was then admitted to the chamber. To ensure a positive flow of hydrogen, it was passed out of the chamber through a 20-foot long tube and burned for safety purposes.

Before the actual braze was made, a small "tattletail" was used to verify the lack of oxygen. This amounted to a current being applied to a stainless steel heating coil and observing if any oxidation resulted. When the chamber was free of oxygen, the power was applied to the braze-heating elements. The temperature was observed visually by means of an optical pyrometer. Upon approaching the melting temperature, visual observation was used. Power was left on for 10 to 20 seconds after the braze alloy was first observed to melt and then shut off. The reason for the short time duration was to assure a minimum grain growth of the Inconel thermocouple leadout sheathing.

This entire procedure, except for the initial checkout of the furnace chamber, was repeated for each braze. After completion of the final braze, the entire unit was removed from the furnace. Each braze joint was then helium-leak checked. A visual inspection of each braze joint was also conducted. The completed seal block unit is shown, in Figure 6-9.

Once this process was developed, only one fabrication problem occurred. During the next-to-last braze operation on IFA Number 4 a lead cable severed. This happened while at brazing temperature and in the brazing zone. An investigation was conducted to determine the cause. It was found that the particular lead cable was slightly under stress while being held in place. The brazing heat weakened the lead cable causing it to twist off. The severed lead cable was that of the upper tightener rod dummy thermocouple. A repair was effected by drilling out the pass-through sleeve, inserting a new thermocouple and remaking the seal block braze.

The development work required to establish the seal block braze procedure was difficult. The main problem was the development of a suitable containment. A hand brazing operation was attempted. This proved unsuccessful due to the inability to maintain the proper temperature. This was evidenced by porosity, poor penetration and excessive grain growth. The main problem then was to contain the seal block area only. This also was not feasible due to the inability of maintaining a good vacuum. Hydrogen could not be used either, for these same system leaks presented an explosion hazard. One alternate, that of fabricating an L-shaped furnace to accommodate the entire IFA and leadout cable assembly was adopted. A vacuum system was used to pump down this entire furnace. This was unacceptable because the pump-down time to achieve 2×10^{-8} torr was 30 hours. A second pump was added which significantly reduced the cycle time. This solved the problem until an IFA was actually inserted. It was found that thermocouple insulators, leadout cables and the lower portion of the IFA continued to out-gas. The final satisfactory solution was found by using a hydrogen (reducing) atmosphere instead of a vacuum. It was at this time that the tattletail concept was devised and implemented. The optimum elapsed time was 10 to 20 seconds (at melting temperature) to insure required penetration and no significant grain growth.

4.3.3 Tightener Rod Thermocouple-to-Rod End Plug

The tightener rod thermocouple-to-tightener rod end plug braze was made (see Figure 4-25). The first step in fabrication was to prepare the end plug by welding [Tungsten Inert Gas Process (TIG)] the pass-through sleeve on the outside. The end plug was then sent to the machine shop to have the pass-through sleeve machined flush with the inside diameter of the end plug. The inside junction was then TIG welded and the pass-through sleeve weld helium-leak checked. Again the end plug was sent to the machine shop to have the thermocouple hole drilled in the pass-through sleeve. The completed unit was fired in a hydrogen atmosphere of 1000°C for 30 minutes. See Figure 4-26 single pass-through sleeve.

The chromel alumel thermocouples were prepared for brazing by dental sandblasting in the area of the braze. The thermocouple was threaded through the drilled hole with the probe end allowed to project 3/32-in. through the hub. This entire unit was then placed in the hydrogen furnace (see Figure 4-24). The molybdenum heating filaments were put in place after the Nicrobraz Number 50 alloying compound was affixed to the junction. Current was applied to the filament until the brazing alloy was observed to flow. Power was left on long enough to form a continuous fillet of braze material between the thermocouple and the pass-through sleeve. In no case was the power left on for more than 20 seconds after the melting was first observed. The braze joint was helium-leak checked to assure a good braze.

Figure 4-25. Thermocouple Pass Through the Tightener Rod

Figure 4-26. Coolant Thermocouple Pass Through Braze

No fabrication problems were encountered with this braze or similar brazes once the fabrication procedure was developed. The only step which was somewhat critical was the forming of the bend in the thermocouple lead cable in the confines of the end plug.

The initial attempt to make these brazes was to hand-torch braze the pass-through sleeve into the end plug. This was then to be followed by a hand-torch braze of the thermocouple to the pass-through sleeve. Various hand techniques, brazing alloys and technicians were tried; all with the same unsatisfactory results. Any hand-torch method could not provide the finite temperature control needed to obtain the required penetration while not causing gross sheath material grain growth. The next attempt was to weld the pass-through sleeve into the end plug only from the outside. Depth of penetration could not be assured because the pass-through sleeve was inserted into the end plug at a steep angle. On the underside of the angle it was difficult to get the welding torch in position. On the exposed side, the metal acted as a heat sink causing lack of penetration. It was not until the double-weld approach was tried that the required weld-wall thickness was attained uniformly. The final process to be developed was that of the hydrogen furnace braze of thermocouple-to-pass-through sleeve. Although this required considerable time, it was a straightforward testing procedure varying the braze parameters until the desired results were obtained. The length of time required to develop this process was in large measure due to the turnaround time for evaluation of the braze samples.

4.3.4 Extension Tube to Tightener Rod Lower End Plug

The original design specified the flowmeter lead cable to be brazed directly to the lower tightener rod-bottom end plug. This was found to be impractical inasmuch as the braze junction was inaccessible. Therefore, IPO recommended and received Engineering's approval to braze an extension tube into the bottom end plug and then braze the flowmeter lead cable to the sleeve. This section is concerned with the braze between the extension sleeve (tube)-to-end plug.

Both parts, the bottom end plug and extension sleeve, were hydrogen fired for cleaning in a reducing atmosphere at 1000°C for 30 minutes. The sleeve was then positioned in the end plug and this assembly was put in the six-inch vacuum furnace. The braze was made using Nicrobrazz Number 30 with the power source being the Lepel high frequency generator. An induction heating coil was employed which transmitted the heat to the wall of the end plug. This particular braze lent itself to this type of heating inasmuch as the unit acted as its own heat sink. The power was applied and the temperature raised until a melt of the brazing alloy was observed. Power was left on for 20 to 40 seconds after this, until the uniform flow of brazing alloy was observed. The completed braze was allowed to cool in the vacuum furnace until it reached ambient temperature. It was then removed and the braze inspected and leak-checked.

No fabrication problems were encountered in the making of this braze.

As explained previously, a design change required the use of the extension tube. Originally the braze of the flowmeter leadout cable-to-the-end plug was in an inaccessible recessed area. It was difficult to obtain a good braze by means of the external induction heating coil. It was also found difficult to use molybdenum heating elements within the vacuum system because they could not be placed uniformly down inside the end plug recess. This caused uneven heating and unsatisfactory brazes. At first, hand-torch methods were attempted to braze the lead cable to the end plug. As explained earlier, hand-torch methods were unacceptable. The use of the extension sleeve and the vacuum braze was adopted. No additional testing was required other than the making of a sample certification braze.

4.3.5 Flowmeter Leadout Cable-to-End Plug Extension Sleeve

After the extension tube has been brazed into the tightener rod-bottom end plug and after the flowmeter subassembly was completed, the flowmeter leadout cable was brazed to the extension sleeve. This was accomplished by threading the flowmeter leadout cable through the extension sleeve. The end plug-extension sleeve subassembly was slid down the leadout cable until in its proper location, i.e., the bottom of the end plug against the spider (Figure 5-2, Part 25). This whole assembly was mounted in the fixture and was then positioned in the hydrogen furnace. The Nicrobrazz Number 50 alloying compound was applied and the molybdenum heating elements placed in position. A hydrogen flow of about 5 cfm was established before the power was applied. The braze joint was brought up to temperature and maintained at temperature for 10 to 20 seconds after the melt started. This assured a full penetration braze joint but

was a short enough time period so as not to cause grain growth. The braze was allowed to cool in the hydrogen atmosphere after which the unit was removed from the furnace (see Figure 4-27). The braze joint was then checked on the mass spectrometer leak detector.

There was one occurrence of difficulty in making this braze. This occurred on the fifth IFA. During the braze operation the leadout cable sheathing at the braze point melted. Under the heat applied, the pressure vented out through the wall of the sheathing. A repair was attempted by brazing over the defect hole but this was unsuccessful in that the braze material flowed into the sheathing and shorted out to ground one leg of the leadout wires. This then required the complete remake of the flowmeter and associated tightener rod end plug.

Very little process development was required for this braze. Once the design change was approved, it was only a matter of making a sample braze. The only potential problem was one of safety concerning the hydrogen flowing out of the open-ended hydrogen furnace.

4.4 WELD JOINTS (TUBES-TO-SPACERS)

In the fabrication of the lower portion of the IFA's, it was necessary to make several weld joints between tubes and spacers, and spacers-to-spacers. These joints were on the fuel extension rods and on the lower and upper tightener rods. All the welds were essentially the same in that they were all made on the glass lathe by means of the tungsten-inert gas procedure. The required welds and reference drawings are listed below.

A. Fuel Extension Rod

1. Bottom End Plug, Figure 5-2, Part 14-to-Tube, Figure 5-2, Part 26
2. Top End Plug, Figure 5-2, Part 15-to-Tube, Figure 5-2, Part 26

B. Fuel Extension Rod Assembly-to-Fuel Rod

C. Lower Tightener Rod—GE Drawing 886D514

1. Bottom End Plug, Figure 5-2, Part 24-to-Tube, Figure 5-2, Part 27
2. Top End Plug, Figure 5-2, Part 22-to-Tube, Figure 5-2, Part 27

D. Upper Tightener Rod

1. Bottom End Plug, Figure 5-2, Part 28-to-Tube, Figure 5-2, Part 10
2. Top End Plug, Figure 5-2, Part 12-to-Tube, Figure 5-2, Part 10

E. Lower-to-Upper Tightener Rod

All welds were made joining Type-304 stainless steel to Type-304 stainless steel except those welds made to the tightener rod tubes. These tubes were of Type-316 stainless steel. The only other difference was in the size of the parts. The large diameter welds were 0.970-in. diameter and were used at the top end of the fuel extension rods. All other welds were 0.875-in. diameter.

All of the weld joints were made to GE Specification 22A1658. This specification required all welds to be machine welds. Both travel and weld current were automatically controlled. Additionally, weld current was recorded. The welding station, procedure and operator were qualified for each weld joint. The shield gas for the fusion welds was welding-grade helium and argon. The shielding gas flow was sufficient to prevent oxidation of the weld and adjacent material. No machining, filing, buffing or brushing was performed on the welds. All welds were visually inspected and were smooth and free of irregularities. Welds were rejected if there was evidence of craters, lack of fusion, undercutting or inclusion of tungsten particles.

Figure 4-27. Flowmeter Lead to End Plug Braze

Figure 4-28. Thermocouple to Tightener Rod Joint

One weld is discussed in detail. To delineate the differences between the actual weld parameters used for making the different welds, a table of parameters (Table 4-3) is included at the end of this section.

Upon receipt of materials, all stainless steel parts were cleaned to GE Specification P4CYP3-S1. This was followed by the passivation according to GE Specification P4AYP1-S2. After this point, handling of these parts required the use of white cotton gloves. The end plug (spacer) was placed in the left-hand head stock of the glass lathe. The tube which was to be welded to the end plug was inserted into the right-hand head stock. The tube was brought into contact with the end plug and seated in the weld preparation. The collets in both head stocks were tightened to securely hold the parts to be welded. A small tube connected to a bottle of helium was inserted into the end plug to provide an internal cover gas. The necessary parameters for making the weld were set. The rotation of the lathe was started and the weld was produced automatically (see Figure 2-11).

Upon completion of the weld, the unit was removed from the lathe. Each weld was visually examined and leak-tested using a helium mass spectrometer leak detector. The maximum permissible leak rate was 2×10^{-8} torr, helium. After leak-checking the rods were cleaned with acetone and sealed in polyvinyl plastic bags to maintain cleanliness.

Prior to each production weld, a sample weld was made. This sample was sectioned and microscopically examined after it was leak-checked. Only if the sample passed examination was the actual weld made. After the actual weld was made, another sample was made. This postweld sample received a leak check and a visual examination.

Upon completion, the technician completed the appropriate quality control certification card. The strip-chart recording of the weld parameters was removed from the recorder and placed in the quality control folder. The finished subassembly was stored in a limited access area until needed for final assembly.

For a detailed description of the different individual assembly sequences, refer to the appropriate heading in Section 5.

No problems in fabrication were encountered once the welding parameters were established and after the process and technicians were certified. The only change in procedure was if the rod had to be straightened as described in Paragraph 5.5.

Table 4-3
WELD JOINT WELDING PARAMETERS

Material	Description/Identification	Gas		Welder Setting*	Recorder Amps*	Start*	Time		Time (sec) Finish*	Time (sec)
		Flow CFH	Spindle Speed*				(sec)	Weld*		
304/304	Fuel Rod-Extension Rod	20	36	8.35	48	8.45	3.0	9.4	21	7.3 3.5
304/316	Tightener Rod: Eng Plug to Tubes	20	38	8.35	43	8.3	3.0	9.1	19.5	7.0 3.5
304/304	Tightener Rod: Upper- Lower-Small Diameter	20	28	9.05	31.5	8.3	3.0	8.0	30	5.1 3.65
304/304	Tightener Rod: Upper- Lower-Large Diameter	20	27.75	9.1	41	9.1	3.5	8.4	30	5.0 3.5
304/316	Tightener Rod: Upper- Lower-Small Diameter	20	28.5	8.4	32	8.4	3.0	8.0	30	4.4 3.5
304/316	Tightener Rod: Upper- Lower-Large Diameter	20	27.5	8.3	31	9.1	3.5	8.05	29	4.4 3.8

* The parameters noted are "glass lathe" or welding machine settings indicating the parameters were controlled rather than calibrated values.

5. SUBASSEMBLY FABRICATION

5.1 GENERAL DISCUSSION

Several subassemblies were fabricated prior to the final IFA assembly work. In some cases the entire quantity of subassemblies required for the project were fabricated at one time, such as the fuel extension rods. Other more complicated subassemblies were batch run, such as the pressure vessel portions. Generally, one individual technician was responsible for making one type of subassembly. Due to personnel transfers, it was occasionally necessary to train new technicians. In some instances subassemblies previously made, had to be remade due to defects and/or spoilage during subsequent operations.

Most of the subassembly work was straightforward assembly and heliarc welding. The pressure vessel portion proved to be more difficult and time consuming because it came under the Nuclear Code Requirements. This required additional testing and documentation. The flowmeter presented a challenge due to it being a new item for the IPO Shop. After the initial learning period, it became a standard item. The subassemblies fabricated fell into four categories and are described as follows.

5.2 FLOWMETER

The flowmeters were made using nine component parts. They were made in accordance with GE Specification 22A1666. There were three sizes of flowmeters as determined by the throat diameter. The largest diameter throat was 1.200-in., the intermediate was 0.960-in. diameter, and the smallest was 0.670-in. diameter. Inasmuch as the assembly sequence is identical for all three sizes of flowmeters only one size will be discussed.

Most of the parts were made from Type-304 stainless steel bar stock, including the 0.020-in. walled inner and outer tubes. The magnet rings and lead cable were purchased items. Other components necessary for the fabrication of the flowmeters were machined parts.

After the inner tubes were machined, they had to be flame-sprayed with an insulating alumina (see Figure 5-1). The outside diameter first was sandblasted, but it could not be reduced by more than 4 mils. The tube o.d. was then flame-spray coated using Metco 105 to a coating thickness of between 3 and 11 mils.

The flowmeter end, and the outer tube, were pressure-fitted together (see Figure 5-2). They were then heliarc welded together as a subassembly (see Figure 5-3). Another subassembly made up for the flowmeter fabrication was the heliarc fusion weld of the flange, Figure 5-3, Part 1-to-the inner tube, Figure 5-3, Part 2. This was done with a special cone shaped fixture which held these two pieces in position. The pass-through sleeve and the guard, for the lead cable, were welded into position. Next the lead cable was threaded through the guard and pass-through sleeve. The small back-fill tube was also welded into place at this time. A torch-braze operation to bond the leadout cable sheath to the pass-through sleeve was made next, utilizing Nicrobraze Number 30 as the braze-alloying material (see Figure 5-4). After completion the braze joint was leak checked.

The next step in the assembly sequence was to determine the north poles of the ring magnets. This was done using a known magnet. When the orientation had been established a small ring magnet and a large one, Figure 5-3, Part 3, were slipped over the inner tube. Next the lead cable was stripped back to bare the wires. The short lead wires are threaded with five alumina insulators and then spot welded to the inner tube (see Figure 5-5). The sheathing of this short lead wire was also spot welded to the inner tube to provide mechanical strength. This short lead wire was formed to fit in the grooves of the magnets prior to the upper end spot welding. Next the short lead wires were connected by tweezer-weld to the long lead cable which had been brazed into the pass-through sleeve. Some 15 alumina single bore insulators are threaded on the lead wires before tweezer-welding to prevent grounding. The area of the tweezer-welds was then potted with Sauerisen compound.

The outer two magnets, again one large and one small in proper orientation, were slid into position over the inner tube. The locking key was put into position and welded to the flange (see Figure 5-6). This holds the magnets in the proper orientation. The final assembly step was to slide the subassemblies into position. No special fixtures were necessary. A fusion weld between the outer tube and the flange was made. A cold-rolled steel bar was inserted into the flowmeter to keep the magnetic flux away from the weld arc as much as possible.

Figure 5-1. Flowmeter Flame Sprayed Inner Tube

Figure 5-2. Flowmeter End to Tube Weld

Figure 5-3. Assembly Exploded View
(Sheet 1 of 4)

Figure 5-3. (Sheet 2 of 4)

Figure 5-3. (Sheet 3 of 4)

Figure 5-3. (Sheet 4 of 4)

Figure 5-4. Flowmeter Brazes and Welds

Figure 5-5. Flowmeter Lead Wire Joint

Figure 5-6. Magnet Locking Key

After the unit was fully assembled, the unit was leak-checked by means of the back-fill and pinch-off tube. If the unit passed the leak-check test, it was put into a glove box and pumped down and helium back-filled a maximum of three times. The back-fill tube was then pinched closed and sealed by fusion welding. When the completed unit was removed from the glove box, the guard tube with the lead cable in it was bent into the required shape.

Two problem areas existed in the fabrication of the flowmeter. The first was making the fusion weld between the inner tube and the end, because of the magnetic flux. This problem was handled by taking extra care in the welding operation. The other problem area was making the spot weld of the lead wires to the outside of the inner tube. The lead wire is small and work hardened. Any excessive bending would break the wires. Extra care during spot welding resolved this problem.

Some minor problems and changes were also evidenced in the fabrication of the flowmeters. The original prints called for the lead cables and the junction of the two lead cables to be sealed with glass. This proved difficult and Sauerisen Number 29 cement was used with Engineering's approval. The lead cable protective tube, was originally made bent to its final shape. It was found that the lead cable could not be threaded through this guard. With Engineering's approval the tubes were remade straight and bent into final shape after the entire flowmeter was fabricated. Due to the flame-sprayed insulation, the magnets would not fit over the inner tube. This problem was solved by grinding four mils off the inside diameter of the magnet.

5.3 PRESSURE VESSEL SECTION

The pressure vessel section is the uppermost portion of the instrumented fuel assembly. This portion comes under the ASME Boiler and Pressure Vessel Code. The California State Code Inspector was required to certify all welds, and that the pressure vessel portion was fabricated to the Code. It was necessary to have an "N" stamp. An agreement was made whereby IPO used the N stamp of APED, San Jose.

The pressure vessel portion was fabricated of some nine major parts plus the Inconel-sheathed leadout cables. It was made in compliance with ASME Boiler and Pressure Vessel Code, Section III, Nuclear Vessels.

All material used on the pressure vessel portion had to meet the Code requirements. It was necessary to provide special handling and storage capability inasmuch as all the material used had to be traceable. Upon receipt of the incoming material, the material certification papers were first checked to assure accuracy and completeness. All parts were dimensionally inspected after which they were cleaned and passivated. The individual parts were then packaged in sealed polyethylene bags for storage until use. The parts were stored in a controlled material cabinet in an isolated area.

The first step was to weld together the bottom bulkhead, Figure 5-3, Part 4 and the pipe section, Figure 5-3, Part 5 in the welding fixture. A Grinnel ring (consumable welding insert), was placed between these two parts. The parts were then tack welded into place. The fusion weld root pass was made next. The top-hat adaptor (Figure 5-3, Part 6) was placed in the welding fixture, again with a Grinnel ring between it and pipe section, Figure 5-3, Part 5. Again the root pass weld was made. At this time the welds were x-rayed for porosity, drop-through and tungsten inclusions. After the welds were x-rayed, the remaining weld beads were made. All welds were made only by a Code certified welder. The welds were then x-rayed per the ASME Nuclear Code. Before proceeding, the x-rays were sent to APED, San Jose, for interpretation by a Certified X-Ray Technician, Level 1.

Concurrently with this welding operation connections of the lead cables to electrical pins were being made. One end of the lead cables were stripped back to expose the wires. The stripped-back end was then sealed using Glyptol. Two alumina insulators were placed on each wire and the wire was bent to fit over the pin connector spade end. Each wire was tweezer-welded to the spade end using no less than three welds. This operation continued from the inside pins outward until all wires were connected (see Figure 5-7). At this point the protective cap was tack-welded into place covering the electrical pin-lead cable welds. The lead cable bundle clamp was then tightened into place and locked by tack welding. The lead cable bundle was also fastened together in several places using twisted stainless steel wire. A continuity check was conducted at this time.

Figure 5-7. Connector Back Face

The individual lead cables were then threaded through the holes in the bottom bulkhead, Figure 5-3, Part 4. They were adjusted to length so that the electrical pin connector at the other end would fit properly in the flange. See Figure 3-5.

This whole subassembly was then placed in the four-inch Lepel vacuum system. The bulkhead brazes were made in one simultaneous operation. After the subassembly was removed from the vacuum system, it was helium-leak checked and a continuity check was performed. Another lead cable bundle clamp and holder were tack-welded into position on the top end of the pipe, Figure 5-3, Part 7.

The next operation to be performed was to weld the Marman flange, Figure 5-3, Part 8-to-the top-hat adaptor, Figure 5-3, Part 6. A Grinnel insert ring was again used and the root pass weld was x-rayed. The final welding beads were made and a full series of x-rays was taken. Figure 5-8 depicts this unit at this stage of progress. It should be noted that the Marman flange-electrical pin connector and the top end have protective devices in place. These were kept in place at all times except when working directly in that area.

The top hat, Figure 5-3, Part 9 was welded to the top-hat adaptor, Figure 5-3, Part 6. To ensure a positive flow of welding gas on the inside of the pressure vessel section, two 1/8-in. holes were drilled, one into the pipe, Figure 5-3, Part 5 and the other in the top-hat adaptor. After x-ray inspection the 1/8-in. hole in the top-hat adaptor was closed by plug welding. The plug weld was x-rayed and leak-checked.

This assembled unit was pressure tested at a pressure of 268 psig in the presence of the State Code Inspector. To prevent damage to the electrical pin connector seal weld, the pressure was equalized on both sides of it. This is illustrated in Figure 5-9. A continuity check was made to assure undamaged electrical connections.

The other 1/8-in. purge hole was then plug-welded, leak-checked and x-rayed. Using an electrical connector alignment fixture, the connector was positioned to the flange. The connector was then rotated into its proper position and held in place. The connector was tack welded in four places to prevent rotation. The entire unit was then placed into a controlled atmosphere glove box. It was evacuated three times and back-filled with helium each time. The closure fusion seal weld of the connector-to-flange was made, see Figure 3 8. When the completed assembly was removed from the glove box, a final continuity check was made and the electrical pin protector block put in place.

The final connector pin check was made. The electrical pin connector was placed on an optical comparator where the alignment of each pin was checked and corrected as required. Prior to joining the pressure vessel section to the lower segment, the lead wires were temporarily mechanically joined. Heat was applied to generate an emf and thereby verify the correct material usage and proper lead wire-to-pin connection.

The complete data package was assembled and reviewed by the State Welding Inspector prior to his signing the release.

The only developmental problems of the pressure vessel portion were establishing the weld parameters for making the lead wire-to-electrical pin terminal tweezer welds. A considerable amount of time was required to develop these welding parameters. Weld quality was sensitive to weld current. This problem was overcome and no fabrication problems in this area were encountered.

Several isolated fabrication problems were encountered with the making of the pressure vessel portions. The first one was a choice to build the pressure vessel section as a separate subassembly. The 180 degree return part of the pressure vessel section originally called for two 90 degree-bend pipes to be welded together and then to the flange and the pipe. To make the pressure vessel section a separate subassembly the top-hat design was conceived and design changes made.

On the pressure vessel, the closure weld of the 1/8-in. purge holes was a problem. The 1/8-in. weep hole was left as the last closure. It was found to be next-to-impossible to get a good closure weld because the welding torch heat expanded the gas on the inside of the pressure vessel section and would bubble out through the molten weld material. It was agreed to use a special weld and insert a tight fitting plug. This was done in accord with the ASME Code Interpretation Case 1361-1. This weld was leak-checked and dye-penetrant checked.

"TOP HAT" FORGING TO BE WELDED

Figure 5-8. Pressure Vessel Section

Figure 5-9. Pressure Test on Code Section

The final problem encountered was that the electrical pin connector alignment fixture held the connector by two 0.040-in. pins, see Figure 5-10. To gain required azimuth adjustment strength a second alignment fixture was made, see Figure 5-11. This fixture filled the requirements satisfactorily.

5.4 TIGHTENER ROD EXTENSIONS

The tightener rod extension was a stainless steel tube, Figure 5-3, Part 10, closed at both ends with an end plug and filled with stainless steel pellets. Through the center of the tightener rod extension of 0.3125-in. tube, Figure 5-3, Part 11 served as a guide sleeve for the lead cables coming from the flowmeter and coolant thermocouples.

The tightener rod extension was made up as a subassembly.

All parts were dimensionally inspected upon receipt or after machining, after which they were cleaned and passivated to GE Specification 22A1666. The first fabrication step was to braze the 0.3125-in. diameter tubes into the bottom end plug. This was a hand-torch braze using Nicrobrazo Number 50 as the braze material. A leak check was performed to assure the quality of the braze.

Eight short stainless steel pellets were loaded into the bottom end of the tightener rod outer tubing. A special tapered stainless steel pellet was then inserted. The end plug, with the brazed-in tube, was then inserted into the semiloading outer tube until the outer tube fit snugly over the weld preparation on the end plug. The joint was then tack welded in four places. From the open top end, two long stainless steel pellets were slid into position followed by eight stainless steel pellets and a special stainless steel pellet. A spring was next inserted. The seal was inserted into the top end plug, (Figure 5-3, Part 12) and held in place with the retaining ring. The end plug was then joined to the outer tube while ensuring the inner tube was seating in the seal. This joint was tack-welded in four places.

The entire unit was then put in the glass lathe. A programmed fusion weld was made between the bottom end plug and the outer tube. The upper tightener rod was turned end-for-end, and the fusion weld of the outer tube-to-top end plug was made. For the exact parameters used in making these welds, see Section 4.4, Weld Joints, of this report. These welds required full penetration and the outside diameter of the welds could not exceed 0.880-in. After the subassembly was completed, it was leak-checked, sealed in a plastic bag and stored until needed.

IPO had some difficulty in establishing the weld parameters. Weld parameters were developed, speed of rotation, weld amperage, weld time period and electrode position and the results verified by metallography and x-ray. Prewelding and postwelding samples were used to maintain high quality welds throughout the fabrication cycle.

At one point, it was noticed that the tubes supplied had pits and corrosion defects on the inside diameter. After a considerable amount of testing, it was found that intergranular corrosion was present. An entire new supply of tubes was obtained.

The special tube with a reduced diameter portion used for the extension rod was obtained from an outside explosive forming vendor.

The only significant design change on the tightener rods was the replacement of the boron carbide fill. The fill was replaced with stainless steel pellets. Also at this time, the stainless steel wool was deleted as a filler.

5.5 FUEL ROD EXTENSION

The fuel extension rods Figure 5-3, Part 13 were stainless steel tubes, with an increased diameter over part of the length filled with stainless steel pellets, and capped at either end with tapered end plugs. These rods connected the top of the fuel rods and the rod housing. They also provided a sealed containment through which the fuel thermocouple lead cables passed.

Two fuel-rod extension rods were required per instrumented fuel assembly. The outer tubing was received from an outside explosive forming vendor requiring only cutting-to-length and cleaning.

Figure 5-10. Electrical Pin Alignment Fixture

Figure 5-11. Second Electrical Connector Pin Alignment Fixture

The first operation was to hand-torch braze the two inner tubes into the bottom end plug Figure 5-3, Part 14 using Microbraz 50 brazing alloy. All the stainless steel pellets were next placed into their proper position over the small inner tubes. This amounted to twenty three pellets. The spring was then placed into position. The outer tube was slipped over the pellets until it was seated at the weld preparation on the bottom end plug. The outer tube was then tack welded in four places to the bottom end plug.

The top end plug Figure 5-3, Part 15 had the seal, Figure 5-3, Part 16 inserted. The retaining ring was then snapped into place. This top end plug subassembly was then placed into position interfacing with the outer tube while the two small inner tubes were guided through the seal. After the outer tube was properly seated on the weld preparation of the upper end plug, it was tack welded in four places.

Prior to being placed in the glass lathe for welding, a sample weld was made of the bottom end plug weld. After the weld sample passed the quality control check, the fuel extension rod was placed in the welder. The production weld was then made. A postwelding sample was also made and inspected to ensure a quality weld. The actual welding parameters used are listed in Section 4.4, Weld Joints.

The weld parameters were now reset to make the larger diameter top end plug weld. Again a preparatory weld sample was made and evaluated. The extension rod was placed in the lathe and the weld made. A postwelding sample was again made.

The completed unit was leak checked using the mass spectrometer helium leak detector. A dimensional inspection conducted to ensure that the assembly was straight to within 0.005-in. per foot. If the unit did not meet this specification, the assembly was placed in vee blocks and straightened by applying a controlled uniform load. During this straightening operation, a dial indicator was measuring the amount of deflection caused by the applied load. In this manner no greater force or straightening action than necessary was applied to the extension rod. Upon completion of the straightening, the fuel extension rods were encased in a polyvinyl plastic bag which was sealed.

The only developmental problem on the fuel extension rods was that of making satisfactory tube-to-end plug welds. The final weld procedures and parameters used in making the fuel extension rods are listed in Section 4.4, Weld Joints.

The only fabrication problem encountered was that of maintaining the 0.005-in. per foot straightness procedure described early in this section.

The only significant design change on the fuel rod extensions was the replacement of the boron carbide fill with stainless steel pellets. This change caused no problems and represented a cost improvement.

6. ASSEMBLY

6.1 ELECTRICAL CONNECTOR

The job scope included six detachable electrical instrumented fuel connectors (see Figure 2-8). These form a connecting unit between the 20-pin connector on the fuel rod bundle and the Conoseal flange which is part of the outer head of the reactor vessel. These units were made up of a 2-in. x 1-1/4-in. pipe reducer and a 180 degree return, 2 Conoseal joints, one of which has the 20-pin female connector seal welded into its face. Approximately 30 feet of cable (a bundle of 10 thermocouples) extended from the other Conoseal outlet flange to be connected to readout equipment.

6.1.1. Code Requirements

In each instrumented fuel connector housing there are three welds that were made to conform to the ASME Boiler and Pressure Vessel Code, Section III, Class A, 1963, and to receive a code stamp with the N symbol. The California State Inspector read and evaluated x-rays of each weld witnessed 275 psig pneumatic pressure tests; and checked vendor's material certifications to be assured they comply with ASME Code.

6.1.2 Weld Fixturing

A weld fixture was designed and built in IPO Shops (Figure 6-1). This fixture held the two Conoseal joints in their respective positions while a 2-in. x 1-1/4-in. pipe reducer and a 180 degree return fitting were welded in between. Both Conoseal fittings were placed in machined receptacles and held fast by clamps.

6.1.3 Connector Make-Up and Test

All thermocouple leadouts were stripped back 1/2-in. on one end, approximately 7/8-in. on the other. These leads were cleaned with a dental blaster. A resistance reading was taken at this time. All electrical insulation had a resistance reading greater than 500 megohms.

Both ends of the thermocouple were then sealed with glass powder melted with a heating torch.

All thermocouple wire leads were identified and tagged according to their alloys. Six assemblies were built. There were five different lead-wire alloys and four different wiring combinations involved.

Ten wires were then bundled together with four 1/8-in. thermocouples in the middle and six 1/16-in. thermocouples placed around the perimeter of the middle thermocouples.

The bundle of thermocouples was then threaded through the back shell and held away from the bench by a holding fixture. One piece of 3/16-in. long double bore alumina insulator tubing was threaded on the two legs of the thermocouple. Several small single bore tubing lengths were threaded on the wires until approximately 3/16-in. of bare wire was left exposed. These wires were then tweezer-welded to their respective spade on the 20-pin socket insert (see Figure 6-2). The back shell was slid down over the socket insert and clamped in place by two screws in the back shell clamp. The socket insert was then tacked to the back shell. It was necessary to strengthen the clamp design by building a larger clamp for the end of the back shell. One-half of this clamp was welded to the back shell clamp. The thermocouple bundle was then clamped tight using a heavy C clamp and the sides were fusion-welded.

The entire 20-pin lead circuits were checked for resistance and the readings were recorded.

6.1.4 Fabrication

With the back shell clamped and welded into place, the bundle of 10 leads was threaded through the welded connector housing, starting at the Conoseal flange with the back shell receptacle. Extreme care was taken during threading to keep the proper orientation of the 20-pin connector with the Conoseal flange by means of an ink mark. A fixture was made (Figure 5-9) to maintain this alignment to the Conoseal flange in final welding. Another in-process resistance reading was taken to ensure proper resistance prior to final Conoseal-to-back shell fusion seal weld.

Figure 6-1. Instrumented Fuel Connector Weld Fixture

Figure 6-2. Electrical Pin Connector Back Side

At the Conoseal outlet-flange end of the connector housing, a special clamping device was installed (Figure 6-3). This clamp is similar to the one on the back shell. One-half of this clamp is designed to fit and be welded inside the periphery of the flange approximately 1/8-in. in from the edge. The purpose of this clamp was to hold the thermocouple bundle rigidly in the center of the flange so no additional stress would be applied to it in fabrication or reactor operation.

6.1.5 Quality Control

All parts for the fuel connectors furnished by outside vendors and/or IPO Shops and all weld fixtures were inspected to ensure conformance to drawings and specifications.

In-process resistance readings on the thermocouples were taken on a step-by-step basis to make sure no moisture was getting past the glass seals into the insulation.

6.1.6 Code Test and Inspection

Radiographs at 0 degrees and 90 degrees were taken of all ASME Coded welds in the connector housing. All six housings were pneumatic pressure tested to 275 psi. The outlet flange has a proof test of 770 psi (see Appendix 1).

The California State Code Inspector approved the IPO engineers set-up for inspection and testing of the housings. The Code Inspector checked the material certification, approved the x-rays and pressure test, and acknowledged that all the requirements of the applicable standards code have been fulfilled. Housing units were issued identification plates with the symbol N as covered in the ASME Code.

6.1.7 Fabrication Problems

Wire breakage was one of the biggest problem areas. There are four significant reasons for this:

- a. The small amount of space available to connect the wires by tweezer welding.
- b. The slightest movement during tweezer welding would break the wires.
- c. The sealing of the thermocouple ends with glass caused some embrittlement of the wires.
- d. The original clamping device on the back shell only gave about 3/16-in. clamping area. This was not adequate to hold ten thermocouples, and allowed them to move with the clamp as a fulcrum. It was possible to break wires inside the back shell. The new clamp corrected this by providing approximately 1-3/4-in. clamping area at the end of the back shell.

In assembly of one unit, two leads, J and K were reversed. This crossing was not detected until final checkout, and the unit was accepted as built. This problem was solved by changing the corresponding leads in the matching IFA.

In the original design the alignment fixture that held the 20-pin connector in the proper orientation applied the total strain of the bundle and back shell to 2 pins. To prevent breakage of the ceramic insulator, a plastic insert was made. This distributed the stress to all of the pins which are supported by a ceramic insulator seal.

Some of the 20-pin connectors were out of tolerance positionally and were sent back to the vendor for rework.

The clamps in the original design on the back shell did not close 100%. They were machined in the groove section to give clearance for the closing.

6.2 INSTRUMENTED FUEL, TIGHTENER, AND LEAD SYSTEM

6.2.1 Code Requirements

All welds in the instrumented fuel assembly between bulkhead Figure 5-3, Part 4 and the 20-pin connector, with the exception of the 20-pin connector seal weld, were made and tested in accordance with Section III – Class A

Figure 6-3. Special Thermocouple Lead Holding and Centering Clamp

Nuclear Vessels of the ASME Code. The bulkhead was the lower termination of the Coded section and the Conoseal flange (Figure 5-3, Part 8) was the upper part. The Conoseal flange formed the junction point of the IFA inside the vessel to the instrumented fuel connector which was a part of the outer head of the reactor vessel.

In this portion of the instrumented fuel assembly, all conditions of the ASME Code were met as interpreted by the State Code Inspector. The following discussion delineates the Code requirements for the SEFOR IFA's.

The first condition to be met was to have the Nuclear N stamp. The authorization to have the N stamp required established necessary procedures, existence of quality control systems, and certified technicians who had passed the ASME qualification examination. Therefore, an agreement between APED Quality Control, IPO Shop Operations and the State Code Inspector was entered into, whereby APED would provide the controls and systems necessary for IPO to manufacture the Coded section. To assure the quality of work, APED provided certain services as later described.

All welds were made by a certified welder. X-rays of the welds were required. APED provided assistance in developing the procedures and parameters for the taking of the x-rays but all x-rays were taken at IPO Shop Operations by IPO personnel. Inasmuch as IPO did not have a Class I Radiologist, the x-rays had to be sent to APED Quality Control for interpretation. A letter stating the acceptance of the welds and x-rays was provided to IPO by APED.

Documentation for the Coded section was required and was reviewed by the State Code Inspector. The required documentation consisted of:

- a. Material Certification Papers
- b. Welder Certification Papers
- c. Blueprints of all Components
- d. Description of all Welds and Brazes
- e. Letters of Approval for X-rays of the Welds
- f. Design Calculations
- g. Partial Data Sheet

Before the Partial Data Sheet was approved, the State Code Inspector reviewed the entire list of requirements. Furthermore, he witnessed the pneumatic testing of the completed unit. This test required the unit be pressured to 268 psig with room temperature helium and exhibit no detectable leaks, (see Figure 5-8). At this point the unit was accepted by the State Code Inspector but the Partial Data Sheet was not signed until just prior to shipment of the entire IFA. The Partial Data Sheet was signed by a representative of General Electric Co., Vallecitos Nuclear Center, IPO. Just prior to packaging, the Nuclear N stamped nameplate was affixed to the Conoseal flange. A pencil rubbing of the nameplate was included in the documentation folder. The completed document folders are stored and maintained in the Nuclear Compliance Archives.

6.2.2 Welding Fixtures

The entire IFA was made up of stainless steel parts welded together. Very few of the parts could be subassembled before the actual IFA fabrication commenced. Only four separate subassemblies were fabricated.

The first subassembly was the flowmeter (Figure 2-5). The flowmeter did not require any special fixtures or jigs. Although there were four major welds required on the flowmeter, they were all made by hand, utilizing only standard shop devices such as vee blocks, vises, etc. The flowmeter was so designed that the parts and weld preparations provided their own inherent alignment characteristics.

After the flowmeter subassembly was completed, the tightener rod subassembly was fabricated and joined to the flowmeter. No special fixtures were required for this operation. A special alignment procedure was written to assure the alignment of the coolant thermocouple probe tips. The tightener rod was placed in a trough. A dial indicator was used to ensure alignment after which the end plug-to-tube was tack welded. The unit was then moved to the glass lathe and the fusion weld made (Figure 2-11). This same trough-and-dial indicator arrangement was used to assure thermocouple-spider alignment.

The third subassembly was the fuel extension rod. No special weld fixtures were required inasmuch as the welds were made on the glass lathe.

The last subassembly to be fabricated was the pressure vessel portion (Coded section). No special fixtures were required to make the first Coded weld. The bulkhead was tack welded to the pipe in four places to hold it in position. This unit was then put in a motorized rotating chuck and the root pass weld was made followed by the final weld beads. The second weld, between top-hat adaptor and pipe, was made in the fixture shown in Figure 6-4. The bulkhead and flange were positioned to assure the proper bulkhead hole alignment. The weld between the top-hat adaptor and Conoseal flange was made in the jig shown in Figure 6-5. This fixture held the pipe and the flange in proper alignment and position. The last weld, between top hat and top-hat adaptor was also made in the fixture shown in Figure 6-5. This time, the fixture was laid on its backside so that the pipe piece was in a vertical position.

The assembly and fabrication of the IFA consisted of starting with the flowmeter-tightener rod subassembly and continually welding on piece after piece. One complete assembly fixture was developed to accomplish this. Two slotted gauge tables were precisely aligned and secured. Upon this, various small fixtures were added to hold and support the IFA during its fabrication. At the lower end of the IFA, a support was made to hold the flowmeter and the two fuel rods and the tightener rod. Another support was provided in the center section of the fuel rod area. This is seen in Figure 6-15. An overall view of the support and welding fixtures is presented in Figure 2-1.

The portion of the welding fixture used for assembly of the parts in the seal block area are shown in Figure 6-6. This is a closeup view showing the seal block in position during fabrication. The ribbon area, between the fuel rod portion and the upper IFA section, is shown in Figure 6-7 and Figure 6-8. This part was the only changeable part of the entire IFA assembly and weld fixture. The length of the ribbon area was dependent on the location of the IFA within the core. Namely, the long ribbon area indicated the IFA was to be located near the center of the reactor core whereas a short (one wave) ribbon portion was used for the IFA to be inserted on the outer periphery of the core.

The upper portion of the IFA welding and assembly fixture is shown in Figure 2-1, Figure 6-9 and Figure 6-10. The uppermost part of the welding fixture is more clearly seen in Figure 6-10.

It was in this area that the Coded portion (pressure vessel) was welded to the lower assembly.

It should be noted that the above described tables and welding fixtures were also used as reference data for all inspections.

6.2.3 Sequence of Assembly

Six instrumented fuel assemblies were made; i.e., one of each 197R243G1, -G2, -G3, -G4, -G5, and -G6. They were made in the following sequence of group numbers: 5, 6, 4, 1, 3 and 2.

The IFA group number differed from another group number in essentially three ways. The first was that different thermocouples were used in the fuel rods. Although this made a large amount of difference as far as the fuel rods were concerned, it had no significant bearing on the assembly of the IFA. One major difference was the size of the flowmeter (there were three sizes of flowmeters). The other major difference was the position of the IFA in the reactor core. Groups 5 and 6 were located at the outer edge of the core and thereby required essentially no ribbon lead area joining the fuel rod portion to the upper IFA segment. On the other hand the Group 1 and Group 2 IFA's were to be located near the center of the reactor core and needed long ribbon areas to the extent of having three full-wave forms. Although these were significant differences the assembly sequence remained the same for all six IFA's.

Figure 6-4. Weld Fixture

Figure 6-5. Weld Jig

Figure 6.6. Housing Area of Assembly Fixture

Figure 6-7. Ribbon Area of Assembly Fixture

Figure 6-8. Ribbon Head Forming

Figure 6-9. Splice Area Assembly

Figure 6-10. Upper Assembly Section

Prior to starting final assembly, the following subassemblies were retrieved for use; the flowmeter, tightener extension rod, pressure vessel portion, and fuel rod extension rods.

Final assembly progressed simultaneously along several lines. When the two completed fuel rods were received from the Plutonium Laboratory, an incoming inspection was conducted. The resistance and continuity of the thermocouples was checked along with the straightness of the fuel rod. In cases where the non-straightness of the fuel rods was beyond the tolerance of ± 0.005 in. per foot, the rods were straightened. Straightening was accomplished as explained in Paragraph 5.5. After the straightening operation, the fuel rods were sent back to the Plutonium Laboratory for profilometry checking. Upon their return, the thermocouples were again checked for continuity and resistance. On IFA's 4 through 6 an additional thermocouple quality control check was conducted. This entailed the use of a heat source being applied to each of the fuel thermocouple hot junctions. The emf output of all conceivable combinations of thermocouple legs was recorded. The results were then analyzed and the thermocouples positively identified to prevent any misconnection to the pressure vessel portion at a later time. When this test was completed the fuel rods were taken over to the glass lathe for welding to the fuel extension rod subassembly. The top end of the fuel rod was inserted into left-hand head stock of the lathe. The thermocouple leadout cables were threaded through the fuel-rod extension rod which was then inserted into the right-hand head stock of the glass lathe. The extension rod was seated on the weld preparation of the fuel rod and the collets were tightened down on both head stocks. The weld parameters were checked and/or set and the weld joining the fuel rod and fuel extension rod was made (see Figure 2-11 and Figure 5-3, Point 19). It should be noted that a preweld and postweld sample were made with each weld joint. The completed unit was then removed from the glass lathe and leak-checked. This unit was then dimensionally checked, and when required, straightened as previously described. The fuel-rod extension rod subassemblies were sealed in plastic bags and stored until needed in conduit containers.

While the fuel rod fabrication was progressing, work was also being done on the flowmeter-tightener rod assembly. The first step was to weld the pass-through sleeve into the tightener rod bottom end plug. The center extension sleeve and the coolant thermocouple were then brazed into this bottom end plug. This entire procedure was previously explained in Section 4.3, High Nickel Braze Joints.

When this was completed, the tightener sleeve nut was placed over the end plug and the tightener rod bottom end plug was welded to the spider (Figure 6-11). This was a heli-arc fusion weld. The only consideration necessary in making this weld was to assure that the coolant thermocouple was properly aligned with the spider. This was done by bisecting the angle between fuel rods and then tack welding the spider and end plug together and rechecking before making the fuel weld. The coolant thermocouple was required to be positioned midway between the fuel rods which were added later.

Next the flowmeter was attached to the spider. This was accomplished by passing over the bottom of the flowmeter and the spider ring (Figure 5-3, Part 29). At the same time the flowmeter leadout cable was passed through the center of the spider. The spider ring was fusion welded to the spider and the ring flange was spot welded in twelve places to the outside of the flowmeter while its face was 0.010-in. from the spider ring (see Figure 4-27). This mechanism allowed 1/8-in. lateral movement of the flowmeter in relation to the spider and the entire IFA.

The high nickel braze of the flowmeter leadout cable to the tightener rod bottom end plug extension sleeve was made next. The procedure for making this braze was explained in Section 4.3, High Nickel Braze Joints.

The fabrication of the lower tightener rod started with the loading of the beryllium oxide pellets. The pellets in the lower half were loaded over the flowmeter and coolant thermocouple leadout cables. The lower tightener rod was then installed over the beryllium oxide pellets and seated on the weld preparation of the bottom end plug. Four tack welds were then made to hold these two parts together. The remaining beryllium oxide pellets were next loaded into the tightener rod over the leadout cables.

Four inches of the lower tightener sleeve was a separate part to allow working room to make the tightener rod welds. This short segment was later welded into place. This shortened lower tightener sleeve was then slid into place over the lower tightener rod. The lower tightener rod top end plug was put in position and the lower tightener rod

Figure 6-11. Spider to Bottom End Plug Weld

seated on the weld preparation of the end plug. This junction was held together by four tack welds. The entire unit was then placed in the glass lathe and the bottom end plug-to-tightener rod weld made. The lower tightener sleeve was then slid down (where the four-in. section would have been if not removed) and the top end plug-to-rod weld made. Again preweld and postweld samples were made in sequence with the actual weld.

As explained in Section 5.4, Tightener Extension Rod, this part was already fabricated. See Figure 6-12 for an exploded parts view. This included the two coolant thermocouples brazed into the tightener extension rod lower end plug. At this point, if a dummy thermocouple was required it was inserted. Insertion involved sliding the dummy thermocouple down the center of the tightener rods and measuring the amount of insertion to locate the hot junction. A dummy thermocouple was either in the lower or upper tightener rod at its center. They were so located as to be at the same elevation as the coolant thermocouples. The tightener extension rod (upper tightener rod) was then welded to the lower tightener rod in the glass lathe per the description given in Section 4.4., Weld Joints.

The upper tightener sleeve was then slid over the tightener rod extension. The upper tightener sleeve was positioned, aligned and joined by fusion welding to the lower tightener sleeve. This tightener sleeve assembly was then slid upwards as far as the coolant thermocouples would allow and the four-in. sleeve segment was inserted and welded to the tightener sleeve unit. The entire sleeve was slid down into position and welded to the tightener sleeve nut which was free to slide back and forth along the length of the tightener rod bottom end plug. Upon completion the entire tightener rod assembly was leak-checked.

The completed fuel rod-extension rod subassemblies (two per IFA) were then placed into the IFA. This amounted to the nose (bottom) end of the fuel rods being inserted into the spider sockets. These were not welded into place (see Figure 6-13). The rod holder (Figure 5-3 Part 30) was placed in position after the thermocouple lead cables from the two fuel rods and the tightener rod were threaded through the rod holder. These three rods were then welded to the rod holder. See Figure 6-7 which also shows the completed seal block brazes.

All the leadout cables were then formed to conform to the print requirements to fit within the housing (Figure 5-3, Part 31). Previously the seal block (Figure 5-3, Part 21) had all the pass-through sleeves welded into place and leak-checked. The leadout cables were then threaded through the pass-through sleeves in the seal block and the seal block slid down into position adjacent to the rod holder. The seal block was then welded onto the rod holder. Each thermocouple leadout cable had a specific hole that it had to pass through in the seal block. The fuel thermocouple leadout wires always occupied the Numbers 1 and 2 holes and either the 8 and 9 holes or 7 and 8 holes dependent upon the number of dummy thermocouples employed. The subsequent seal block brazes were made as described in Section 4.3, High Nickel Braze Joints. The entire unit was returned to the major assembly fixture.

The housing was then welded into place, to rod holder and seal block (see Figure 6-14). The tightening sleeve actuator subassembly, lifting stud and gusset (Figure 5-3 Parts 32, 33 and 34) were welded to the housing cover, Part 35. In the housing cover, a 1/8-in. diameter tube was inserted for back-fill and leak-check purposes. This entire subassembly was then fusion welded to the seal block and to the housing (Figure 5-3, Part 31) (see Figure 6-15). This portion was backfilled with helium and the small tube pinch-sealed, cut off and closed with a fusion weld. The two actuating arms, Figure 5-3, Part 36, were then welded to the rod holder, on the bottom and on top to the tightening sleeve actuator assembly, Part 37.

The lead guide, Figure 5-3 Part 37, was then welded to the rod holder. The lead wire cables exiting from the seal block brazes were then formed over the ribbon area (Figure 6-8). After the lead wire cables were formed over one wave or hump, they were clamped down and the process continued on the next trough and then the next hump until the entire ribbon area forming was completed. Upon completion of forming the cable had the same profile shape as the lead guide. Additional lead wire cable forming was necessary to form a figure S. This figure S expansion shape was later covered with a perforated sheet metal guard, Figure 5-3, Part 38. The lead cables were then threaded through Figure 5-3, Part 20. This operation was done while in the main assembly and fabrication fixture. It was necessary because the length and location of the lead wire cables with respect to the bulkhead, Part 32, was critical.

Figure 6-12. Exploded View of Tightener Rod Extension

Figure 6-13. Fuel Rod Spider Engagement

Figure 6-14. Upper Housing to Rod Holder Weld

Figure 6-15. Assembly with Lifting Lug in Place

The entire IFA unit was now removed from the assembly fixture. The bulkhead and lead cable section was placed in the four-in. vacuum system (see Figure 6-16). The braze of the lead cables-to-bulkhead was then made in a vacuum furnace. This braze was identical to the Figure 5-3, Part 4 bulkhead braze on the pressure vessel portion (as explained in Sections 4.3 and 5.3) with the exception that special vacuum seals had to be provided around the lead cables. This special seal was made of cast RTV* Silicone Rubber. All parameters and procedures were the same as for the pressure vessel braze.

After the Figure 5-3, Part 20 braze, the unit was removed from the vacuum furnace and leak-checked for integrity. The entire unit was then reinstalled on the main assembly fixture. The bends in the lead wires in the figure S area were reformed inasmuch as they were bent out of shape to permit entry to the vacuum furnace. After the bends were reformed, the lead shield, Figure 5-3, Part 17, was welded into place over the ribbon lead area of the figure S. The two Figure 5-3, Part 39 lead clamps, were then joined together by a support bracket. See Figure 6-17. The shield guide was welded to the guide end, Figure 5-3, Part 40. This unit was then welded to the slotted pipe (Figure 6-18). Upon completion the fuel thermocouples were checked out by means of the heat source test described in Section 6.2.5 and 6.2.8 of this report. This test also verified again the identification of each lead wire cable and the thermoelement phasing.

Prior to the splice between the lower portion of the IFA and the pressure vessel subassembly, the half-pipe, Figure 5-3, Part 42, was welded to Figure 5-3, Part 20 and pressure vessel bulkhead, Part 4 (see Figure 6-19). This was done to ensure the proper overall length and to add rigidity to the spliced area. This half-pipe was welded into position so as to form the bottom half of this area. The lead cables protruding out from the lower bulkhead, and those from the pressure vessel bulkhead, were not cut to length. This was done after the leadout cables were formed so as to provide mating with the proper cable from the other end. All the lead cables then had the sheath stripped back to expose a sufficient length of leadout wire to provide for thermal expansion. Alumina insulator beads were strung on the wires to prevent electrical shorting. The splice area support spacers (one at each end of the splice) were inserted and the lead cables inserted into the recesses in the spacers. Stainless steel wire was wrapped around the leadout cables to prevent them from pulling out of the spacer recesses. The leadout wires were then resistance-welded together to form a continuous electrical circuit from the electrical pin connector in the Conoseal flange down to each sensor. Each weld joint required a minimum of three tweezer-welds to ensure conductivity and mechanical strength.

After all splice welds were made, another full heat source check on the fuel thermocouples was made (see Figure 6-20). This time the generated emf was measured at the electrical pin connector in the Conoseal flange. The splice area was then potted using Sauerizen 29 material. An open area right where the tweezer-welds were made was left void of potting compound to allow for thermal expansion. The potting compound was allowed to cure for 24 hours. The other half-pipe, Part 32, was welded into position. The entire splice area was now totally sealed except for the small pinch-off tube in the second half-pipe. By means of this tube, the splice area was evacuated for 24 hours and then helium-leak checked. The unit was then back-filled with helium and the tube pinch-sealed, cut off and seal welded. Finally, the alignment cam positioner, Figure 5-3, Part 43, was welded into place thereby completing the fabrication procedure of the SEFOR Instrumented Fuel Assembly.

The heat generated from the welding in the splice area caused the upper segment to warp out of shape. To correct this difficulty, heat was applied by means of an acetylene torch and then clamps were used to force the unit back into the alignment tolerance. The final Quality Control Check and Acceptance Test was conducted as explained in Section 6.2.5. Only after the successful completion of these tests was the N stamped nameplate affixed to the connector flange.

6.2.4 Fabrication

The concept followed for the fabrication of the instrumented fuel assemblies was one of having all possible machining done prior to the actual start of assembly. This concept was employed with only one planned exception. All other required machining was caused by either design changes or rework.

* GE Trade Name

Figure 6-16. Lead Cable Bulkhead Braze

Figure 6-17. Lead Cable Clamps and Support Bracket

Figure 6-18. Lead Flex Area Shield

Figure 6-19. Splice Between Lead Bulkheads

GEAP-13713

The only planned machining required during IFA fabrication was that necessary to complete the pass-through sleeves of the tightener rod end plugs. This amounted to boring out the pass-through sleeve flush with the inside diameter of the end plug. Also, after both internal and external welds were made on the pass-through sleeve, the hole for the thermocouple was drilled.

Two late design changes required some machining. The first necessitated the removal of about 1-3/4-in. of material from the end of the lead wire shield, Figure 5-3, Part 17. This was done to prevent the shield from hanging-up while being inserted into the reactor core. The other was reworking the handling stud, Figure 5-3, Part 18, to conform to the dimensional requirements of the print.

Machine work was required to make weld samples. These weld samples were used as preweld and postweld samples for the tightener rod and fuel rod welds. On certain occasions it became necessary to do machining work to repair portions of the IFA. Several of these situations were the machining to open the seal weld on the electrical pin connector, drilling open the weep hole in the pressure vessel portion, and removing the welds on the flowmeter to remove the outer tube and bottom plug. In each case, the machining and repairing of the unit made total unit remakes unnecessary. In all such cases the repair attempts were successful.

It was advantageous to have the machine shop in such close proximity. Many times a small modification was required on a fixture or device. To accomplish this, it required a minimum of time and effort because the machine shop is adjacent to the development shop. The machine shop technicians were aware of the needs of the development shop technicians and the project.

Welding was an integral part of the entire IFA fabrication. For the details of each weld refer to the IFA fabrication portion of this report, Section 6.2.3.

6.2.5 Quality Control

A quality control system was set up for the SEFOR IFA project. This system was generated around the core of IPO Shop Operating Procedures. Quality assurance and documentation were significant items for the entire project because of the rigid design specifications.

To comply with the ASME Code requirements, a thorough review of IPO quality control systems and procedures was conducted. New or strengthened procedures were written and implemented as a result of the review. IPO's Quality Control Engineer provided assistance and guidance, as well as the audit function to assure a quality product. The SEFOR quality assurance program is herein described.

All material received was inspected to verify the completeness and accuracy of the material certifications. The material was also checked to assure its compliance with the purchase order. In a few instances, the received material did not have complete certification papers and in a few number of cases, the material did not conform to the purchase order and/or specifications.

All material received for use on the SEFOR project was transmitted to the project manufacturing engineer who assured the necessary controls for proper handling and storage. All SEFOR material was stored in a controlled access area.

Prior to any material being issued to the floor, a thorough incoming inspection was performed. The inspections and results of same were documented on the standard IPO Inspection Report (IR) form. Copies of all SEFOR IR's are on file for easy reference.

Inspections were conducted during machining operations, upon completion of machining, on all jigs and fixtures, on in-process work in the assembly area, on the finished product and whenever requested by the technicians or when it was deemed desirable.

Before any work started, both technicians and processes were qualified. In all cases this meant the development of the process parameters. After these were established, samples were made and tested to assure repeatability and conformance to specifications. In some instances very specific process specifications were written whereas elsewhere, letters of engineering approval documented the acceptance of the procedure and the technician. Each time there was a change in personnel, the new technician was certified on that portion of the IFA assembly on which he was to work.

To aid the technician and to assure good quality, a special Quality Control Certification Card (QCC) (Travel Card) system was developed and implemented. These QCC cards were detailed step-by-step assembly sequence forms. They delineated the stepwise assembly sequence plus specifying the relevant blueprint number and control specification. Furthermore, they required that the technician sign and date the card after each significant step. These QCC cards proved to be an invaluable aid to the technician and in assuring the fabrication of a good quality product. In several instances the documentation provided by these cards verified that the required tests and procedures were actually complied with. The original copies were filed with the master IFA folder.

Special systems and procedures were required to satisfy the Code requirements on the pressure vessel portion. These requirements were fully discussed in Section 6.2.1 of this report and are therefore not restated here.

After the original Quality Control Plan and System were developed and in use, it was found that certain other tests and checks would be beneficial in assuring a quality product. Due to the inability of assuring the fuel thermocouple identification during fuel processing and fabrication, a special heat source test was conducted. This amounted to applying a heat source to the fuel thermocouple hot junction and obtaining the emf output of all possible thermoelement pair combinations. These data were then analyzed to ensure the proper thermocouple labelling and subsequent connecting. This test was conducted after the completed fuel rods were received from the Plutonium Laboratory, just prior to making the splice between the lower section and the pressure vessel portion and after the splice welds but before closure. This additional testing completely eliminated the problem of misconnecting sensor leadout wires.

Another special test devised after the original quality control plan was instituted was to check the phasing and correctness of the leadwire cables used in the pressure vessel portion. This test amounted to connecting the two wires of a lead cable together. Heat was applied to the connection and the wire material and pin connection were verified by the phasing of the emf output.

Whenever there was a change in process required or a manufacturing change in the product made, a Deviation Report (DR) was completed. Deviation reports also documented the as-built conditions of all the instrumented fuel assemblies. Before proceeding with the change, the deviation reports were approved by both Engineering and Manufacturing.

All design changes were documented by Engineering Change Notices (ECN). In the course of the fabrication well over 100 ECN's were issued and instituted. A significant number were issued upon Manufacturing's request to afford dollar savings and quality improvement.

A final Quality Control (QC) check was made of the completed IFA just prior to its packaging and shipment. This was an Engineering-witnessed test conducted jointly by APED Quality Control and IPO Shop Operations Inspection. Engineering acceptance of the final QC check signified its acceptance of the product and its release to make shipment.

One final check was made. This consisted of installing two accelerometers in the inner shipping container. This was done to ascertain the forces actually incurred on the IFA and IFA shipping containers while in transit from Vallecitos Nuclear Center to Fayetteville, Arkansas. The accelerometer values were recorded by means of polaroid photographs and forwarded to Engineering for evaluation.

6.2.6 Code Test and Inspection

The Code requirements of test and inspection were explained in detail in Section 6.2.1. All test and inspection requirements were met to the satisfaction of APED Quality Control and the State Code Inspector.

6.2.7 Fabrication Problems

There were three general problems encountered in the fabrication of the SEFOR IFA's. One was the maintaining of the proper identification of fuel thermocouples from the time they were built until they were connected to the pressure vessel portion. The heat source test combined with the chemical etching on the sheathing proved feasible but it was time consuming. Another problem was in welding the pass-through sleeves to the seal block. This was a hand-torch method and it was very difficult to ensure a specified penetration weld in such a confined area. This was finally overcome by redesigning the weld preparation as documented on the latest revision of the print. The last problem area was the splice junction of leadout cable wires. Although three tweezer-welds were used to join any two wires, this area was one of the sensitive operations in the IFA fabrication.

Five deviation reports were issued on IFA Number 2. The first one was concerned with the angular deviation of the inlet coolant thermocouple being misoriented by approximately 5 degrees. The tolerance allowance was ± 2 degrees. This problem did not have any detrimental effect on the IFA itself, but it did cause the tightener sleeve to rub against the thermocouple hot junction. To alleviate this problem, the slot in the tightener sleeve was opened up by hand-filing the slot. Engineering accepted this procedure and in operation this change caused no problems.

The second deviation report documented that the seal weld of the electrical pin connector was made before the pressure vessel portion final weep hole was welded closed. This made it almost impossible to close the weep hole in the normal plug weld fashion. Many attempts were made but the internal helium gas expanded during welding and caused gross porosity in the weld. It was only after the weld design was changed to a fillet weld that the problem was solved and the unit accepted.

In the process of verifying the integrity of the bare wire thermocouple by means of a neutrograph, the tungsten tubing appeared to be misoriented. Further investigation showed that the 45 degree angle cut was rotated out of position by about 70 degrees. The potential danger from this situation was that the bare wire alumina insulators could slide down and possibly allow the exposed thermoelement wire to short out against the tubing. After careful analysis it was decided to use the unit "as is."

After the IFA was completed, it was determined that there was too much bow in the pressure vessel portion. The specification requirements were 0.030-in. Total Indicator Reading (TIR) with the actual deviation being 0.090-in. TIR. It was decided to cold-work it by means of a hydraulic press to straighten that portion. The TIR was reduced to 0.050-in. which Engineering decided to accept inasmuch as there was clearance for insertion. Furthermore, the pressure vessel portion became work-hardened causing the straightening to be more difficult.

One IFA was at the reactor site when it was determined that the thermocouple leadout wires were incorrectly connected to the lead cables in the pressure vessel portion. This condition was revealed by the heat source test. The IFA was returned to Vallecitos Nuclear Laboratory (VNC) to effect a repair. The repair consisted of opening the half-pipe section, cleaning out the potting compound, opening the tweezer-welds and redoing the splice after the thermocouples were reidentified by means of the heat source test.

The third IFA had only one deviation. The chrome/Alumel leadwires for a coolant thermocouple were connected to the wrong electrical pin terminals in the pressure vessel. They were directly reversed to what they should have been.

IFA Number 4 had minor problems, errors and changes. None of the problems were irreversible or uncorrectable. The first problem encountered was that of the thermocouples being mislabelled. The thermocouples labels from one fuel rod were on the thermocouples of the other fuel rod. This was a minor problem inasmuch as the heat source test was already implemented. Another problem associated with the thermocouples was that the upper sheathing was nicked and scarred. The grooves did not exceed 0.009-in. in depth and it was agreed to accept the thermocouples "as is."

During the making of the seal block brazes, the leadout cable of the upper dummy thermocouple became severed at the braze area. This problem was rectified by drilling out the old lead wire cable and inserting an entirely new thermocouple down into the upper tightener rod. The lead cable was then threaded through the seal block and rebrazed successfully. The only attributable cause for this defect was that in the clamping of the lead wire cable an internal stress was established. In the subsequent heating for brazing, the sheathing must have stress-relieved itself by twisting and thereby becoming severed.

During the fabrication of the pressure vessel portion, the certified welder noticed a small amount of weld drop-through after making Weld Number 4. In an attempt to remove it by means of a power hand grinder, his hand slipped. This action severed one leadout cable and scarred two others. A sealed splice was successfully effected. No repair was necessary or made on the two marred cables. This unit checked out satisfactorily.

It was on this IFA that Engineering decided to reduce the length of the lead wire shield. This was done to assure clearance of the IFA during insertion into the reactor core. Accordingly the shield had 1-3/4-in. removed from the end nearest the figure S area of the lead cable bundles. This change was also documented by an Engineering Change Notice. This change was made on all IFA's.

The last deviation noted was weld bead buildup on the welds between Figure 5.3, Parts 41 and 20, 20 and 42, 42 and 4, 4 and 5. The buildup exceeded the outside diameter of the pipe which made it unacceptable. The weld buildup was filed down to the outside diameter of the tube, and the IFA passed the final QC check.

The fifth IFA had two discrepancies, both concerning thermocouples. On the outlet coolant thermocouple, no emf output could be measured. An investigation revealed that the alumel leg was broken (open) with the break occurring in the spliced area. The unit was later repaired.

The other problem was that one leg of the bare wire thermocouple was grounded out. This was accepted since a single grounded point on a thermocouple will not change the emf response.

6.2.8 Sensor Lead Checks

Constant surveillance of the fuel temperature sensors was required due to their inherently delicate nature. The philosophy of checking sensor leads after each major or significant operation associated with the sensor leads was established and enforced. Two levels of tests were conducted, dependent upon the point of progress of fabrication. The highest level test was to perform a heat source test on the fuel sensor hot junction and measure the generated emf from all possible combinations of thermoelement wires. This test took about eight hours and accordingly was relatively expensive. The other test consisted only of a resistance and continuity check requiring less than one hour.

As explained in the Thermocouple Fabrication Section, there were many sensor checks conducted throughout the assembly sequence. As these have been previously detailed, they will not be reiterated here, but will rather start with the sensor tests during fabrication of the IFA.

When the completed fuel rods were received by the Development Shop from the Plutonium Laboratory, a sensor resistance and continuity check was conducted. This was done to assure the integrity of the sensor wires. The resistance values were compared to those recorded prior to shipment of the weldment from the Plutonium Laboratory.

After the fuel rod was straightened, the unit was sent to the Plutonium Laboratory for a profilometer check. Upon its return to the Development Shop, another resistance and continuity check was made. In addition, a full heat source check was made to ensure the sensor integrity and functionality, and its identification was verified. The heat source test procedures have been explained previously and will not be restated here. The sensor leads were positively identified by chemically etching their respective label on the end of the Inconel sheathing. The positive thermoelement was also identified and labelled. The location of the markings were so placed that this portion of the sheathing was removed when the sensor lead was cut to length in the splice area.

After the IFA was completed through the seal block brazes, a resistance and continuity check was made. Again this was done to assure the integrity of the sensors before additional labor was added to the IFA.

Just prior to making the splice of the sensor leadwires to the pressure vessel portion leadwires, a full heat source check was conducted. Immediately after making the splice but before the splice area was potted, another heat source check was made. At this point, the entire length of the leads was checked by reading out the generated emf's from the electrical pin connector pins. Figure 6-20 shows this test. This was also the last point-in-time where any significant sensor repairs could be made. After the potting of the splice area it was essentially impossible to effect any sort of repair.

One last set of tests was performed just prior to release and shipment of the IFA. This test consisted of a resistance check, continuity check and a megohm check.

The results of all tests were documented and recorded on the quality control certification card or on one of the special report forms. Periodically additional resistance and continuity checks were made. These were made if a special situation developed whereby the additional test appeared beneficial. The fabrication of a high quality product was paramount at all times and the additional steps and checks were taken to assure high quality.

7. PACKING AND SHIPPING

7.1 LICENSE REQUIREMENTS

The U. S. Department of Transportation (DOT) issued Special Permit (SP) number 5873 for the shipment of the Instrumented Fuel Assemblies from VNC, Pleasanton, California to the SEFOR site at Fayetteville, Arkansas. The permit was issued December 23, 1968 and was extended to expire December 31, 1972. All IFA's were shipped during this permit period. The shipments were designated Fissile Class III, with not more than one package per motor vehicle permitted.

7.2 SHIPPING BOX DESCRIPTION

The authorized packaging consisted of an instrumented fuel assembly secured to a transport fixture, which was secured within an inner wooden container (see Figure 7-1), 17-1/2 in. by 37-3/4 in. by 159 in. long. The inner container was reinforced by multiple 1-1/4-in. wide vertically and horizontally wrapped steel banding (see Figure 7-2). The inner container is positioned by cushioning material within an outer wooden container (see Figure 7-3) 35 in. by 50-1/4 in. by 184 in. long. The total package weight was 1590 pounds.

The outside of each package incorporated a seal, which was not readily breakable and which was evidence that the package was not illicitly opened.

The authorized contents of each package was not more than 1.3 kilograms of fissile material as $\text{PuO}_2\text{-UO}_2$ with approximately 20 percent PuO_2 in depleted uranium oxide, containing 8 percent Pu-240, in the form of pressed pellets contained in two sealed stainless steel fuel rods which are a component of the instrumented fuel assembly.

The outside of each package was plainly and durably marked "DOT SP 5873" and "FISSILE RADIOACTIVE MATERIAL" in connection with and in addition to the other markings and labels prescribed by the DOT regulations.

7.3 PACKING SEQUENCE

Prior to the final quality control checkout of the IFA, the transport fixture was prepared for shipping. All support areas and clamp brackets were padded with rubber gasket material. The gasket material was held in place by using a rubber cement (see Figure 7-4).

After the QC check, additional padding was placed around the flowmeter portion of the IFA. Three men were required to place the IFA into the transport fixture. Three men were used so as not to put unnecessary strain on the leadout wires between the lower and upper portions of the IFA. All clamp retaining pins were inserted after the clamps were closed providing positive holding action (see Figure 7-5).

A special aluminum block was fabricated to fit over the electrical pin connector to prevent damage to or bending of the pins. This device was held in place using the captive bolts in the pressure vessel flange.

The IFA in the transport fixture was then placed in position in the inner shipping container (see Figure 7-1). The inner shipping box would accommodate any one of the three sizes of IFA's with the relocation of the holddown bolts. The holddown bolts were welded to toggle-banding clamps which were secured next. The pressure vessel portion of the IFA was additionally held by support blocks.

When the IFA was fully secured, the electrical pin protector was removed and a final continuity and resistance check was made. After the protector was reinstalled, the IPO Radiation Monitor checked the IFA. If at this point everything was in order, approval to close and secure the inner shipping box was given.

The inner shipping box was secured by banding. A 1-1/4-in. wide steel band was used. These bands were placed on 9-inch centers in both the vertical and horizontal planes. Those in the horizontal plane were put on first and never had to be removed for subsequent shipments. The bands were tightened and by using the closing clips, secured in place.

Figure 7-1. IFA Secured Within the Inner Container

Figure 7-2. Inner Container Reinforced by Steel Banding

Figure 7-3. Inner and Outer Containers with Cushioning Material

Figure 7-4. Transport Fixture with Padded Supports

Figure 7-5. Loaded Transport Fixture, Clamps Secured

Two half-inch braided wire slings were used to lift the inner shipping box and place it in the outer shipping box. These slings were left in place so that the inner box could be extracted from the outer box at SEFOR without damage to either shipping container. The actual insertion was done by a fork lift truck (see Figure 7-3) but considerable assistance was necessary to properly align the inner box prior to insertion. Also, it was found necessary to use sheet metal pieces to prevent the styrofoam side padding of the outer box from becoming damaged by being forced down under the inner box.

The outer box was secured with 5/16-in. bolts around the periphery of the top. Four special bolts were made having a drill hole in the head. These special bolts were put in two opposite corners (two at each corner). A 0.035-in. diameter aluminum wire was threaded through the hole in the bolts and fastened by a lead seal. This completed the packing sequence.

The closed shipping container was turned over to Transportation. Although Transportation used various trucks, they were all of the open flatbed type. The shipping container was secured to the truck bed.

7.4 SHIPPING PAPER COMPLETION

Five documents had to be completed prior to the shipment of any one SEFOR IFA. All of these documents are originated by IPO, Shop Operations with the exception of the first one.

IPO, Program Management initiated the Request for Shipment letter which was sent to the MBA Custodian of IPO, Shop Operations. This letter identified the IFA by the coded section number and referenced the AEC contract and project number, job order and other pertinent information. This letter was issued about three weeks prior to shipment.

Another pre-shipment document was the Form N-2 Manufacturer's Partial Data Report. This report had to be signed by the State Code Inspector and by the GE representative (IPO, Shop Operations Manufacturing Project Engineer). The Form N-2 was not signed by the State Inspector until such time as the entire coded section (Pressure Vessel Portion) was completed. This documentation remained in Shop Operations until the entire project was completed, at which time it was sent to Radiation Protection archives.

Upon receipt of the Request for Shipment letter, Shop Operations initiated and completed the Form 48, Material Balance Area Transfer and the Form 37, Off-Site Transfer (Shipping Document). The Form 374 required the signature of the Radiation Monitor after monitoring the outside of the outer shipping box and therefore could not be completed until just prior to shipment. Upon completion, the Form 374 was given to Transportation for use as their shipping document. They in turn forwarded a copy to the SEFOR Site.

One last item was necessary to be completed prior to transferral of the packaged IFA. This was the completion of the Quality Control Certification Cards. All of these cards had to be reviewed and signed off, including the Packaging and Shipping Card, before Transportation received the IFA. This card also provided the review to assure all paper work was completed.

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APPENDIX A

FUEL ROD FABRICATION

The machined parts required for the fuel rods were made up in the IPO Shop or by outside vendors. The thermocouples were received at Plutonium Fuel Development brazed into the top end spacer (see Figure A-1).

Figures A-1 through A-5 illustrate components and steps in fabricating the fuel rods. As shown in Figure A-1 the thermocouples are received at Plutonium Fuel Development already brazed into the top end spacer. Figure A-6 shows typical standard and long pellets used in the fuel rods. Pellet modification (slots and holes for thermocouple penetrations) were made (see Figure A-7). Fuel samples were submitted to analytical chemistry for gas analysis before and after outgassing.

The fuel pellets were arranged in "stacks" or segment groups after being modified (see Figure A-2). This illustration shows a complete set of fuel pellets as required for a fuel rod. Figure A-3 shows the upper segment loaded with fuel pellets and the spacer pressed into the cladding tube end. The mechanical press for inserting the spacer plug is also shown in this figure. The thermocouple probe extending out of the upper segment will measure fuel temperature in the middle segment.

The special weld setup for making the cladding-to-spacer welds was a special "glass lathe" mounted in a glove box in the vertical position so that the lead cable extending from the fuel rod was hanging down into a pipe containment. The pipe containment provided a well in the bottom of the glove box that extended more than 15 feet into the ground allowing the fuel rod leads to remain straight during the cladding-to-spacer welds.

During production welding on the fuel rods, porosity was found to be a problem on a few welds. Lack of fusion found in a few welds was traced to a varying wall thickness of the lap portion of the spacers.

Figure A-1. Thermocouple Weldment

Changes were made on weld preparation dimensions and tolerance in the fuel tube-to-spacer joint weld to produce welds with less variation in character, and in particular, to eliminate the slight tendency to form small porosities in the welds. Spacers for the fourth, fifth, and sixth IFA were modified by reducing the lap portion of the lap-butt joint to a height of 0.015-in. The wall of the lap was machined to hold the wall thickness dimension within closer tolerance than was previously allowed. The weight of mixed oxide in each instrumented fuel rod is given in Table A-1.

Table A-1
MIXED-OXIDE WEIGHT INSTRUMENTED FUEL RODS
(weight in grams)

Fuel Rod	G1-1	G1-2	G1-3	G1-4	
Upper Section	996.7	1008.5	1007.0	980.6	
Center Section	615.59	612.3	608.8	633.5	
Bottom Section	1394.55	1416.8	1382.9	1345.32	
Fuel Rod	G2-1	G3-1	G3-2	G4-1	
Upper Section	982.0	953.55	945.9	953.1	
Center Section	615.6	606.6	602.7	613.6	
Bottom Section	1384.1	1368.2	1372.7	1382.2	
Fuel Rod	G5-1	G6-1	G7-1	G8-1	
Upper Section	951.9	958.5	960.26	932.5	
Center Section	589.5	606.3	616.0	621.5	
Bottom Section	1343.8	1368.2	1380.96	1349.8	
<hr/> <hr/>					
Assembly VNC	24	25	26	27	28
Fuel Rods	G3-1	G1-1	G3-2	G7-1	G1-2
.	G6-1	G2-1	G4-1	G8-1	G1-3

UPPER AND MIDDLE SEGMENT FUEL

MIDDLE SEGMENT FUEL

LOWER SEGMENT FUEL

Figure A-2. Fuel Segments

Figure A-3. Upper Fuel Rod Segment with Spacer Inserted

TOP SEGMENT

MIDDLE SEGMENT

BOTTOM SEGMENT

BOTTOM END
PLUG

Figure A-4. Fuel Rod Fabrication

Figure A-5. Fuel Rod Fabrication

STANDARD LENGTH PELLETS

LONG PELLET

Figure A-6. Fuel Pellets

Figure A-7. Modified Fuel Pellets

APPENDIX B

HIGH TEMPERATURE FURNACE TEST OF FUEL THERMOCOUPLE PRODUCTION SAMPLE

In addition to extensive development and testing conducted under Task 4.1 and detailed design under Task 9, to specify the proper fuel thermocouples for use in the SEFOR IFA's, a proof test was made on a thermocouple fabricated by IPO to assure that the specifications were met.

The following items were investigated: 1) the high temperature compatibility of the materials of construction actually used, 2) the high temperature performance of the actual thermocouples compared to the development models, and 3) the mechanical integrity of the high temperature portions of the probes after operation at temperatures expected in SEFOR.

TEST PROGRAM

1. Test a thoria-insulated SEFOR fuel thermocouple in an induction furnace to greater than 3600°F for longer than 185 hours. Continuous recording of thermocouple output and periodic calibration with an optical pyrometer is required.
2. After heating, destructively examine as follows:
 - a. Longitudinally sectionalize the hot junction to determine its mechanical integrity and compatibility with the thoria and the interior gas remaining from fabrication.
 - b. Make a transverse section in the hot zone to determine thoria and residual gas compatibility with the W5Re and W26Re.
 - c. Disassemble the transition piece and note mechanical integrity.

RESULTS OF TEST ON TYPICAL FUEL THERMOCOUPLE TO BE USED IN SEFOR

Tests have been completed on a thermocouple produced at VNC, which is similar to thermocouples being fabricated for use in SEFOR. Results have shown that the thermocouple operated satisfactorily for over 200 hours at temperatures greater than 2000°C (3632°F), of which approximately 140 hours were at or above 2200°C (3992°F) (Figure B-1). A maximum temperature of 2570°C (4658°F) was recorded. On completion of the steady-state test, the thermocouple was thermally cycled from room temperature to 2235°C in 1-1/2 minutes and then cycled 5 times between 1000° to 2200°C in 2-minute intervals. Calibration of the thermocouple was performed before and after the thermal cycles, and the results are shown in Table B-1. As indicated, the thermocouple responded extremely well.

Table B-1
THERMOCOUPLE CALIBRATION AFTER THERMAL CYCLING

	Thermocouple (CORRECTED, °C)	Optical Pyrometer (CORRECTED, °C)	Difference (%)
Prior to	2127	2117	+ 0.47
Thermal	1725	1720	+ 0.29
Cycling	1367	1365	+ 0.15
After	2158	2150	+ 0.37
Five	1783	1780	+ 0.17
Cycles	1407	1408	- 0.07

The thermocouple had a 0.140-in. diameter W25Re sheath, was insulated with thoria, and had 10-mil diameter W5Re/W26Re thermoelements. The thermocouple was immersed one inch in an induction furnace, and tested under a vacuum of 10^{-5} to 10^{-6} torr. Temperatures were monitored by a calibrated optical pyrometer and compared to the thermocouple outputs from a potentiometer. The thermoelectric output was semi-continuously recorded with a L/N recorder. The thermocouple was generally within $\pm 2\%$ of the optical pyrometer reading throughout the test.

Metallographic examination of the sheath and thermoelements after testing showed them to be in excellent condition. There was no evidence of porosity in the sheath or deterioration of the thermoelements as previously reported,¹ (Figure 2 and Figure 3). These Results are indicative that the stringent specifications outlined for the fabrication of SEFOR thermocouples are warranted. It further provides confidence that SEFOR thermocouples are being fabricated by competent personnel, and that they should operate successfully.

¹ Novak, P. E., and Asamoto, R. R., *An In-Pile Evaluation of W-Re Thermocouple Systems for Use to 4700°F in SEFOR Fuel*, (GEAP-5468), to be published.

Figure B-1. Thermal History of Test Thermocouple

SECTION 1
100X

SECTION 3
100X

Figure B-2 Radial Cross-Sections of Test Thermocouple

SECTION 1

250X

Figure B-3. Radial Cross-Section of W26Re Sheath Near Hot Junction

APPENDIX C

FUEL THERMOCOUPLE CALIBRATION

The fuel thermocouple wire tungsten 5% versus tungsten 26% rhenium was tested by the supplying vendor for temperature/emf characteristics. The following is an example of test data:

Temperature (°F)	EMF (mV)	Temperature (°F)	EMF (mV)
200	1.306	2200	21.817
400	3.114	2400	23.694
600	5.123	2600	25.486
800	7.223	2800	27.220
1000	9.375	3000	28.917
1200	11.543	3200	30.427
1400	13.687	3400	31.878
1600	15.780	3600	33.316
1800	17.836	3800	34.617
2000	19.856	4000	35.917
		4200	36.936

APPENDIX D
IFA DOCUMENT CONTROL

IFA Document Control	Engineering (Issue)	Engineering (Issue) IPO (Approval)	Engineering (Issue) Pu Laboratory (Approval)	Engineering (Issue) SEFOR (Approval)	IPO (Issue)	IPO (Issue) Engineering (Approval)	Pu Laboratory (Issue)
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SPECIFICATIONS

Functional

- Assembly (22A1666) x
- IFA Installation & Test (22A1789) x
- IFA Electrical Connector Installation
and Test (22A1698) x

Fabrication or Purchase

- Tightener Rod (22A1658) x
- Fuel Rod (22A1650) x
- Fuel T/C (21A2332) x
- Coolant T/C and Lead Cable
(22A1663) x
- Electrical Connectors (VPF S2083-4) x
- Code Pipe and Fittings (22A1729) x
- BeO Pellets (22A1585) x
- Fuel Pellets (22A1545) x
- Insulator Pellets (22A1583) x
- Sheath and Lead Cable Brazing
and Welding (22A1651) x
- Thermocouple Reference Junction-
Compensator (22A1590) x
- Sheathed Lead Cable for Fuel
Thermocouples (22A1657) x

DRAWINGS (PL 191X658)

- Scope x
- Detail x
- Shop x
- As-built x

IFA Document Control	Engineering (Issue)	Engineering (Issue) IPO (Approval)	Engineering (Issue) Pu Laboratory (Approval)	Engineering (Issue) SEFOR (Approval)	IPO (Issue)	IPO (Issue) Engineering (Approval)	Pu Laboratory (Issue)
PROCEDURES							
Process							
• Welding (Assembly)						x	
Procedure 22A2460							
Fabrication Report - Section 4							
Fabrication Report - Subsection 6.2.2							
• Brazing						x	
Fabrication Report - Subsection 2.2.3							
Fabrication Report - Subsection 4.3							
• Forming						x	
Photographs are available showing							
T/C forming fixtures							
• Cleaning (P4CYP3-S1)	x						
Procedure - 22A1666							
• Inspection (Electrical & Mechanical)						x	
22A2423 - Receiving Inspection							
• T/C Fabrication (Fuel)						x	
Procedure 21A2332							
Fabrication Report - Section 4							
• ECN's		x					
• Fabrication Deviation Report (Assembly)						x	
Fabrication Report - Subsection 6.2.5							
• Process Flow Chart (Assembly)					x		
Assembly Sequence Diagram							
• X-ray (Fuel Rod) (Pu Lab 5.1.9)							x
• Helium Leak Test (Fuel Rod)							x
(Pu Lab 5.2.2)							
Qualification							
• Welding (Work Record)						x	
• Brazing (Work Record)						x	
• Assembly (Work Record)						x	

	Engineering (Issue)	Engineering (Issue) IPO (Approval)	Engineering (Issue) Pu Laboratory (Approval)	Engineering (Issue) SEFOR (Approval)	IPO (Issue)	IPO (Issue) Engineering (Approval)	Pu Laboratory (Issue)
IFA Document Control							

QUALITY CONTROL

- Material Control (Assembly) (22A2423)
- Process Control (Assembly)
- Inspection (Assembly including Parts)
- Material Control (Fuel Rod)
- Process Control (Fuel Rod)
- Inspection (Fuel Rod)

x
x
x

x
x
x

Figure E-2 Instrumented Fuel Assembly, As-Built Version

E-4

APPENDIX F

FUEL ROD G7-1 FABRICATION DAMAGE AND REPAIR OPERATION

FABRICATION DAMAGE

During the final spacer weld operation the lead cables became fast in the weld box extension tube and as the welding chuck rotated the lead cables twisted until they were severed approximately 1/2-in. from the end of the fuel rod.

The damage was evaluated: Examination included a continuity check on the two thermocouples (checked out as intact). The evaluation indicated that if a successful splice could be made and if the splice area could be encapsulated and backfilled with helium the fuel rod could be used in an instrumented fuel assembly.

REPAIR PLAN

The repair concept was to first provide a structural support between the lead cables and the fuel rod end spacer. The second step was to make the lead wire splice with the required insulation. The third step was to encapsulate the repair area and backfill with helium.

ANALYSIS

A TIGER V thermal analysis of the SEFOR Fuel Rod Thermocouple Repair Plug was conducted simulating design transient conditions. The largest thermal gradient between the plug and the weld was about 350°F, and it occurred about one second into the design transient. The largest thermal gradient between the inside and outside of the weld was about 200°F and occurred 0.6 seconds into the design transient.

A SNAP thermal stress analysis was performed for each of two conditions. The first yielded a peak effective stress in the weld region of 33,000 psi; the corresponding cycles to fatigue at 1130°F would be about 20,000 psi. The second had a peak effective stress in the weld region of 42,500 psi; here the cycles to fatigue at 1040°F would be about 10,000 psi.

Figure F-1 shows a "detail" of the SEFOR IFA Fuel Rod Thermocouple Repair Plug (Drawing Number 197-R243 G2 ASM). The weld is 20 mils in width. The length of the segmenting plug is 0.250-in., and the disk part is 0.062-in. Since the radius to the center of cylinder wall is 0.420-in. and its thickness is 0.020-in., then the segmenting plug length is $> 3 \times 0.78 \sqrt{rt}$, assuring adequate flexibility of the weld region with respect to the plug.

Figure F-2 shows the nodal arrangement of the TIGER V model used to depict the Thermocouple Repair Plug. Besides the geometry shown in Figure F-2, other input parameters included:

1. Properties of stainless steel (all internal modes)
 - i. $C_p = 0.14 \text{ Btu/lb} \cdot ^\circ\text{F}$
 - ii. $\rho = 0.28 \text{ lb/in}^3$
 - iii. $K = 12.0 \text{ Btu/hr-ft} \cdot ^\circ\text{F}$
2. Heat transfer coefficients
 - i. $h_c (\text{clad-to-coolant}) = 20,000 \text{ Btu/hr-ft}^2 \cdot ^\circ\text{F}$
 - ii. $h_c (\text{plug-to-clad}) = 1000 \text{ Btu/hr-ft}^2 \cdot ^\circ\text{F}$
3. Initial temperature of all modes was 760°F.

F-2

F-3

GEAP-13713

Figure F-1. SEFOR - I.F.A. Fuel Rod T.C. Repair on Drawing 197-R-243 G2 ASM

Figure F-2. TGRV Model of IFA Fuel Rod T.C. Repair Plug

4. The only method of heat transfer was conduction.
5. The coolant was considered to be an infinite sink, input as a table representing the coolant outlet temperature during the design transient. The peak coolant temperature of 1180°F occurred 0.8 seconds into the transient (1135°F @ 0.6 seconds in Case 1, and 1170°F @ 1.0 seconds in Case 2).

Output from the TIGER V analysis yielded a temperature distribution every 0.06 seconds, from 0 to 1.3 seconds. The two select times for the SNAP cases were considered to be the points in time of greatest thermal stress imposed by the transient. They include the maximum thermal gradient between the weld and the plug ($\Delta T_{\max} = 347^{\circ}\text{F}$ at $t = 1.0$ seconds) and through the weld ($\Delta T_{\max} = 196^{\circ}\text{F}$ at $t = 0.6$ seconds).

Figure F-3 shows the model for the SNAP analysis at $t = 1.0$ seconds. Shown also is the location of the peak effective thermal stress, calculated to be 33,000 psi. The cycles-to-fatigue* at the local temperature of 1130°F are about 20,000.

Figure F-4 shows the SNAP Model at $t = 0.6$ seconds. The peak effective thermal stress was calculated to be 42,500 psi, and the cycles-to-fatigue at the weld temperature of 1038°F are about 10,000.

SNAP input for both cases included:

1. Young's Modulus $\cong 2.3 \times 10^7$ psi
2. Thermal Coefficient $\cong 10.3 \times 10^{-6}$ in./in.-°F
3. Internal Pressure = 250 psi
4. Poisson's Ratio $\cong 0.325$ in./in.

REPAIR OPERATION

A detailed repair procedure was prepared including a quality control plan. The procedure had 17 hold-points where sign-off was required prior to proceeding with the repair.

The lead cable was brazed to the part having the support function as well as the end plug for the encapsulated feature (see Figure F-5). After leak-check verification the support end was tack welded to the fuel rod end (see Figure F-6). Insulator beads were placed on the exposed lead wire and the lead wires were phased to the correct thermoelement and resistance welded together.

After a continuity check on the thermocouples verified the splice the encapsulating sleeve (see Figure F-7) was moved into place and welded to the fuel rod end spacer and the support end plug. Following a successful check the encapsulated splice region was back-filled with helium.

TESTING

The repaired fuel rod was leak-checked finally after the helium fill-tube was pinched and welded. The electrical resistance of the lead wire insulation was measured to confirm the absence of moisture in the sheathed cable. The thermocouples were checked by heating at the hot junction region of the fuel rod to show emf response.

* Interpretations of ASME Boiler and Pressure Vessel Code," Case 1331-1 Figure 2, Design Fatigue Strength for High-Alloy Steels.

Figure F-3. SEFOR I.F.A. Fuel Rod T.C. Repair Plug Thermal Stress Analysis (Case 1)

Figure F-4. SEFOR I.F.A. Fuel Rod T.C. Repair Plug Thermal Stress Analysis (Case 2)

Figure F-5. End Plug Braze to Leads, Support Part of End Plug

Figure F-6. Tack Weld of Support to Fuel Rod End and Lead Wire Weld

Figure F-7. Splice Completed Prior to Welding Sleeve

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