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EBR-II ENVIRONMENTAL INSTRUMENTED SUBASSEMBLY XX08: ENGINEERING AND ASSEMBLY

by

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EBR-II Project

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ABSTRACT

Subassembly XX08 is a fueled and instrumented subassembly designed primarily for an ongoing program to investigate the thermal-hydraulic core environment within EBR-II under normal and off-normal plant operating conditions. To a great extent, XX08 resembles its predecessor, subassembly XX07, the major difference being that XX08 contains 58 xenon-tagged, EBR-II Mark-II driver-fuel elements whereas XX07 contained 57 Mark-IA fuel elements. The Mark-II fuel is expected to provide XX08 with an irradiation lifetime three times as great as that attained with XX07, i.e., 9 versus 2.9 at. % burnup. A burnup of 9 at. % is equivalent to about 29,000 MWt days of EBR-II reactor operation, which corresponds to 11 reactor runs at 2700 MWd per run.

Instrumentation within XX08 includes 16 spacer-wire coolant thermocouples with junctions at various axial and radial locations within the fuel-element bundle, six top-of-core-elevation fuel-pin thermocouples, two subassembly-outlet-coolant thermocouples, two permanent-magnet flowmeters for measuring subassembly flow, and two rhodium self-powered detectors for neutron-flux determinations. Signals from the instrumentation are processed and recorded using the EBR-II digital data-acquisition system (DAS).

This report provides detailed information on engineering, design, and assembly of XX08.

I. INTRODUCTION

Experimental Breeder Reactor No. II (EBR-II) was originally designed to demonstrate the feasibility of a liquid-metal fast breeder reactor (LMFBR) as a viable central station steam-electric power generating facility. With this task successfully accomplished, EBR-II's mission was changed to that of an irradiation facility for the United States LMFBR program. In this capacity, EBR-II has had and continues to have many subassemblies containing candidate fuel, control, or structural materials for advanced LMFBR's irradiated within it. For accurate evaluation and interpretation of observed irradiation behavior of these materials, the EBR-II Project periodically attempts to upgrade its characterization and knowledge of the irradiation environment in the reactor. The XX08 subassembly, by virtue of its extensive in-core flow, temperature, and flux instrumentation, was designed to play an important role in this effort to upgrade the irradiation characterization of the core.

With the added sensor capability of XX08 to the overall plant process instrumentation, the Project is also undertaking a natural-circulation program using the EBR-II facility to obtain experimental information typical of overall behavior of an LMFBR plant during protected situations of loss of coolant flow (LOF) initiated by the loss of primary- or secondary-system pumping power, or both. In these and related LOF situations, there is a transition from forced to convective-flow cooling to remove reactor-core decay heat. It is important to understand how the primary, secondary, and steam systems respond to such events. Although dynamic computer codes have been generated to treat various classes of such LOF transients, they have been largely unverified so far because of the paucity of confirming experimental data. The testing proposed for the natural-circulation program is expected to yield safety information of direct interest not only to the EBR-II facility, but also to the LMFBR community in general.

The scope and primary objectives of the XX08 experiment are best summarized as follows:

1. To perform plant-operation and safety-related investigations seeking more reliable operation of EBR-II under normal and off-normal plant conditions.

2. To provide thermal-hydraulic information for LMFBR programmatic support, particularly in the area of transient natural convective flow under LOF conditions.

3. To provide thermal-hydraulic information for better characterization of the EBR-II core environment.

A description and fabrication details of the XX08 subassembly, or as it is otherwise known, the reactor diagnostic probe (RDP), are presented in the following sections. The subassembly was completed in April 1977 and was inserted into EBR-II reactor grid position 5D3 in August 1977. Irradiation began with run 90 and is expected to be continued until the middle of calendar year 1979, with an expected peak burnup of 9 at. % accumulated in about 11 reactor runs.

II. DESIGN DESCRIPTION

Externally, the instrumented subassembly XX08 resembles previous instrumented subassemblies.[1,2] It primarily consists of three major components (see Fig. 1): the subassembly, the extension tube, and the terminal box. The subassembly, depicted in Fig. 2, contains 58 EBR-II Mark-II driver-fuel elements. Sixteen of the driver elements contain thermocouples to measure fuel-pin-centerline temperatures or coolant temperatures within the fuel-element bundle, or both. Two thermocouples above the fuel-element bundle measure the outlet coolant temperature. The subassembly is further equipped with two permanent-magnet coolant flowmeters and two self-powered neutron-flux detectors.

A. Subassembly Design Criteria

Instrumented subassembly XX08 was designed to be compatible with existing EBR-II facilities and to be in conformance with applicable EBR-II operating conditions.

The subassembly was required to be compatible with the Instrumented Subassembly Test (INSAT) facility in which it was to be located. Reference 3 discusses the design and operation of an INSAT facility and the relationships

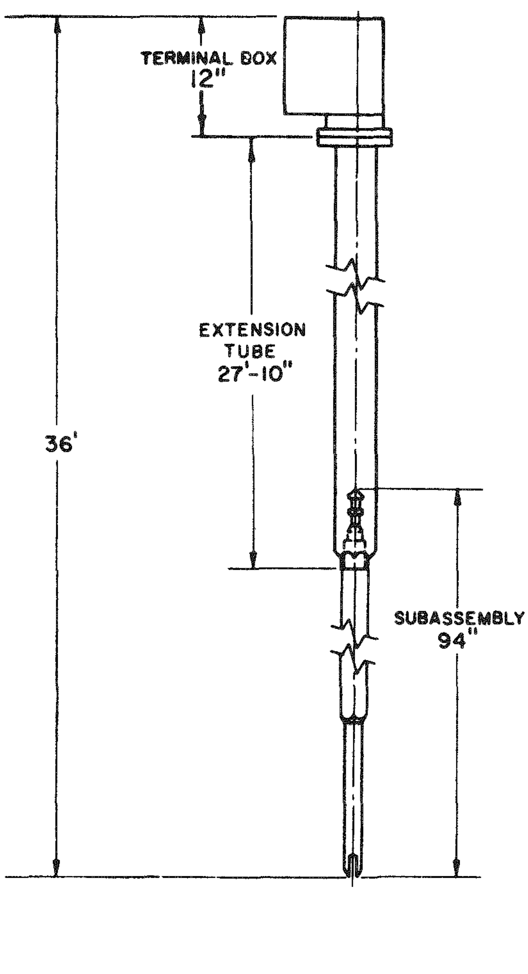


Fig. 1

Arrangement of Instrumented Subassembly XX08, Extension Tube, and Terminal Box. Conversion factors: 1 in. = 25.4 mm; 1 ft = 0.3048 m.

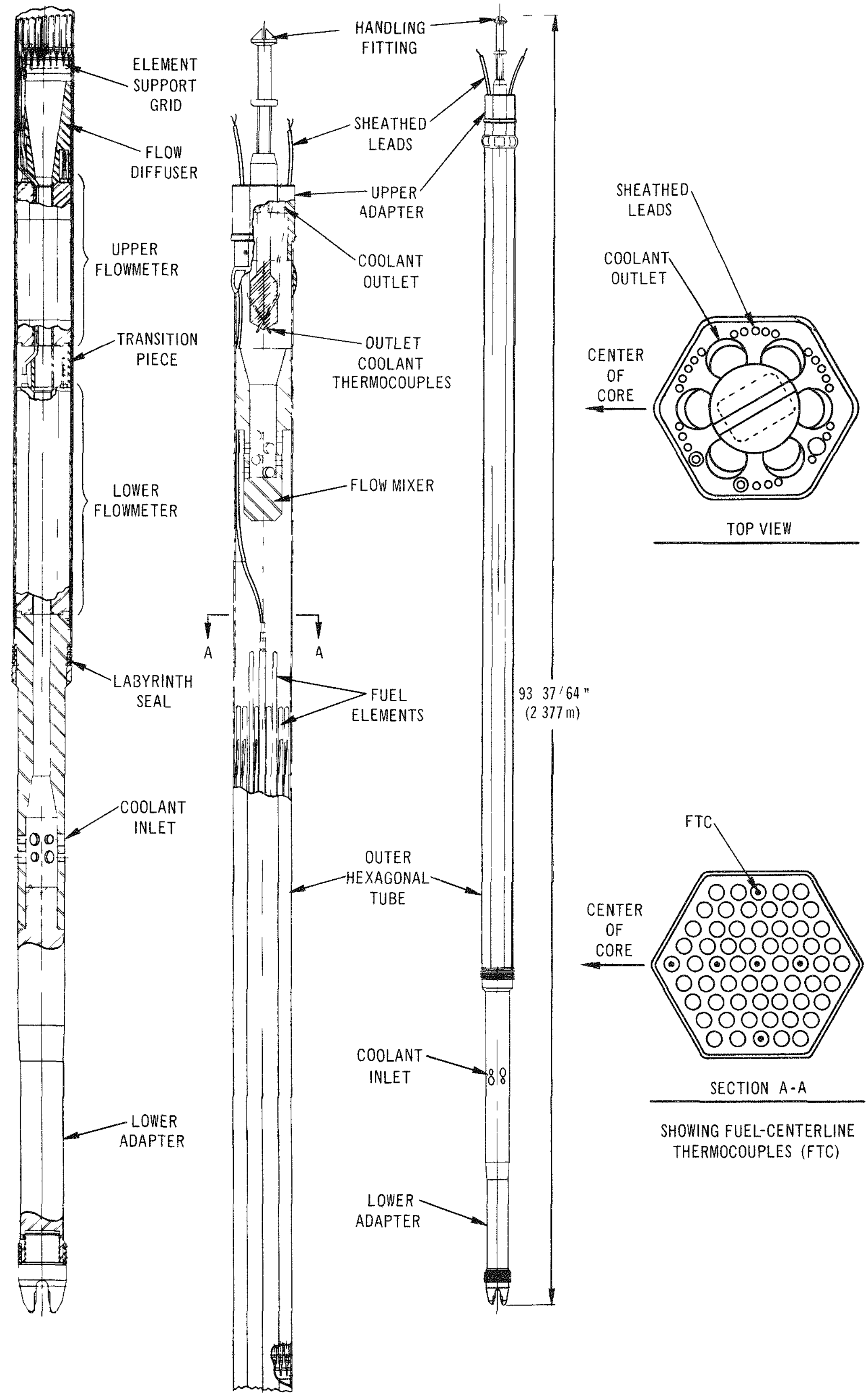


Fig. 2. Instrumented Subassembly XX08

between the facility and the experimental subassembly. Subassembly XX08 was installed in the INSAT II facility, which is in the control-rod No. 2 (5D3) position. As with any experiment to be irradiated in EBR-II, the subassembly was required to be compatible with EBR-II operational capabilities, with EBR-II subassembly-handling techniques, and with the equipment of the Hot Fuel Examination Facility (HFEF). Most important, it could not impose on the safe operation of EBR-II.

Entrapment of any appreciable amount of sodium in the subassembly is prevented by providing for adequate draining of all internal spaces during fuel handling.

In accordance with EBR-II Project requirements, coolant flow through the subassembly is such that the bulk outlet coolant temperature for the subassembly is within 44°C (80°F) of the average outlet temperature for driver-fuel subassemblies surrounding it.

The subassembly is designed for conformance to the following nominal operating conditions:

Total coolant flow rate	3.09×10^{-3} m^3/s (48.9 gpm)
Total power*	481.7 kW
Peak linear power*	27.4 kW/m (8.35 kW/ft)
Bulk inlet coolant temperature	371°C (700°F)
Bulk outlet coolant temperature	516°C (960°F)
Fuel burnup limit**	9 at. %
Reactor residence time (11 runs)**	~29,100 MWd

Safety considerations common to an instrumented-subassembly vehicle were previously presented by the EBR-II Project for safety review. Specific safety considerations pertinent to XX08 were presented in the experiment data package for safety review in accordance with EBR-II Project procedures.

Applicable RDT, ASTM, ASME, and ANSI codes and standards were used in the design and fabrication.

B. Major Components

The three major components of XX08--the subassembly, the extension tube, and the terminal box (see Fig. 1)--are described here.

*Based on estimated fission rates.

**Limited to these values by the EBR-II Experiment Safety Review Group.

1. Subassembly

The subassembly portion is at the lower end of the assembled experiment. It consists of a lower adapter, an outer hexagonal tube housing internal experimental components, and an upper adapter (see Fig. 2). Except for some minor modifications, the outer configuration of these assembled components is the same as that for a standard control rod and is compatible with existing fuel-handling equipment, procedures, and storage facilities.

The lower adapter has inlet holes sized to permit a specified coolant flow through the subassembly (see Sec. III).

The outer hexagonal tube contains a 61-element bundle and two Mark-III permanent-magnet flowmeters. Fifty-eight of the 61 element positions are occupied by Mark-II driver-fuel elements. Of the three remaining positions, one is a sealed tube containing two self-powered neutron-flux detectors, and two are conduits through which pass the instrument leads from the two flowmeters.

Sixteen of the 58 fuel elements are fitted with stainless-steel-sheathed, mineral-insulated thermocouples. Six of the elements have both fuel-centerline and spacer-wire coolant thermocouples, the junctions of which are all 0.83 in. (21 mm) below the top of the fueled section. Ten of the fuel elements have only spacer-wire coolant thermocouples, located as follows: bottom of fueled section, two elements; 5.400 in. (137 mm) above core bottom, two elements; 9.450 in. (240 mm) above core bottom, two elements; 12.670 in. (322 mm) above core bottom, three elements; and 20.250 in. (514 mm) above core bottom, one element. Two outlet-coolant thermocouples are installed above the fuel-element bundle for determining the mean outlet coolant temperature.

The fuel elements, separated from each other by spirally wound spacer wires, are supported vertically and positioned laterally by grid bars. The grid bars, which are welded to the inner hexagonal tube, are spaced to permit the flow of sodium coolant through the element bundle. The weldment of the grid bars and inner hexagonal tube form the element-support-grid assembly shown in Fig. 2. Portions of two grid bars are cut out to allow the passage of flowmeter leads. The flowmeters, one above the other, and a flow diffuser are welded inside the inner hexagonal tube below the grid bars.

Extending upward from the element bundle are 27 instrument leads as follows: 22 leads of 0.062-in. (1.57-mm)-OD stainless-steel-sheathed, mineral-insulated cable emanating from the instrumented fuel elements; one of 0.174-in. (4.42-mm)-OD stainless-steel tube (which contains the two self-powered detectors) emanating from the element bundle; two of 0.125-in. (3.18-mm)-OD stainless-steel-sheathed, mineral-insulated cable emanating from the flowmeters; and two of 0.062-in. (1.57-mm)-OD stainless-steel-sheathed, mineral-insulated cable for the outlet-coolant thermocouples.

The upper adapter and its handling fitting have six coolant outlet holes and 27 smaller holes for pass-through and support of the instrument leads. These holes are placed in a specific pattern to facilitate the lead-cutting operation (see Sec. II.B.4) required for separating the subassembly and the extension tube during removal operations after the experiment's residence in the reactor.

2. Extension Tube

The extension tube (shown in Fig. 3) supports the subassembly throughout its residence period in the reactor and absorbs the torsional reactions during lead-cutting operations. The XX08 extension tube is similar to those used on previous instrumented subassemblies. It consists of an inner oval tube and an outer circular tube, which form a drywell in the annulus between them, and a connecting assembly, which extends through the inner oval tube and supports the subassembly. The lower end of the drywell is sealed against the entrance of sodium by a bulkhead seal-welded to the inner and outer tubes.

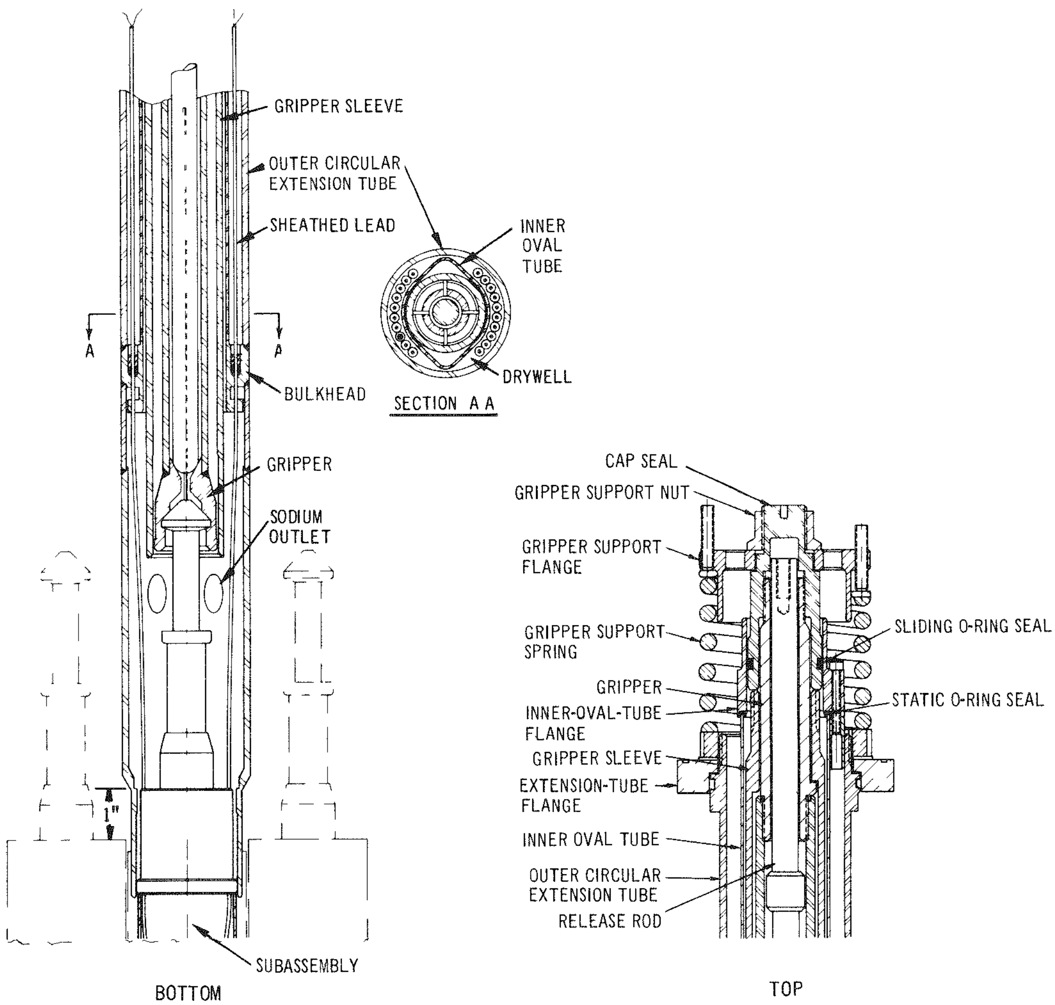


Fig. 3. Extension Tube of Instrumented Subassembly XX08

The metal-sheathed instrument leads emanating from the subassembly pass through holes in the bulkhead and are seal-brazed to the bulkhead. These instrument leads extend up through the drywell to nearly the top of the extension tube. They are held loosely in position, and the resulting slack accommodates the differential expansion that occurs when the relatively cool subassembly is initially inserted into the hot primary-sodium tank and also when the subassembly is raised or lowered during unrestricted fuel handling.

Two thermocouples and three sodium-level detectors are incorporated within the drywell to monitor temperature and to signal the presence of sodium if leakage occurs during the irradiation period. These instruments are described in Sec. II.D.5.

Radiation shielding consists of 40-in. (1.02-m)-long fabricated-metal channels extending downward in the drywell from a point about 48 in. (1.22 m) from the top of the extension tube. These channels form passages through which the instrument leads are routed. The channels do not bear against the leads, so that the leads are free to move during differential expansion.

The metal-sheathed instrument leads are cut back in a staggered arrangement and spliced (see Sec. IV.C.4) to flexible wire in the drywell, above the shielding. Because the metal-sheathed signal cable coming from the lower flowmeter as supplied was shorter than required, an additional length of metal-sheathed signal cable was spliced at a point about 3 ft (0.9 m) above the bulkhead. The splice construction is welded.

The connecting assembly firmly attaches the subassembly to the extension tube and terminal box. It is 27 ft (8.2 m) long and consists of (1) a gripper and gripper sleeve that connect to the handling fitting on the upper adapter of the subassembly and (2) a gripper support flange-and-spring assembly on the top of the extension tube. This assembly compensates for ±0.562-in. (±14.3-mm) differential expansion between the gripper sleeve and the inner oval tube.

In previous instrumented subassemblies, the differential expansion between the gripper sleeve and the inner oval tube and the time required for the components to stabilize at a uniform temperature had been measured. In the installation procedure for XX08, the subassembly was inserted into the hot primary-tank sodium in increments. Each incremental length was held in the hot sodium until the temperatures of the extension tube and its internal components in each length were uniform.

Seals, at the top of the connecting assembly, isolate the terminal box from the blanket gas within the inner oval tube. The seals consist of two O-rings, one a static seal in the inner-oval-tube flange, and the other a sliding seal in the cap seal.

3. Terminal Box

The XX08 terminal box has been used on several previous instrumented-subassembly experiments. Modifications are incorporated to accommodate the XX08 instrumentation.

The terminal box (see Fig. 4) is a sealed compartment in which the extension leads coming from the instrumented subassembly are connected

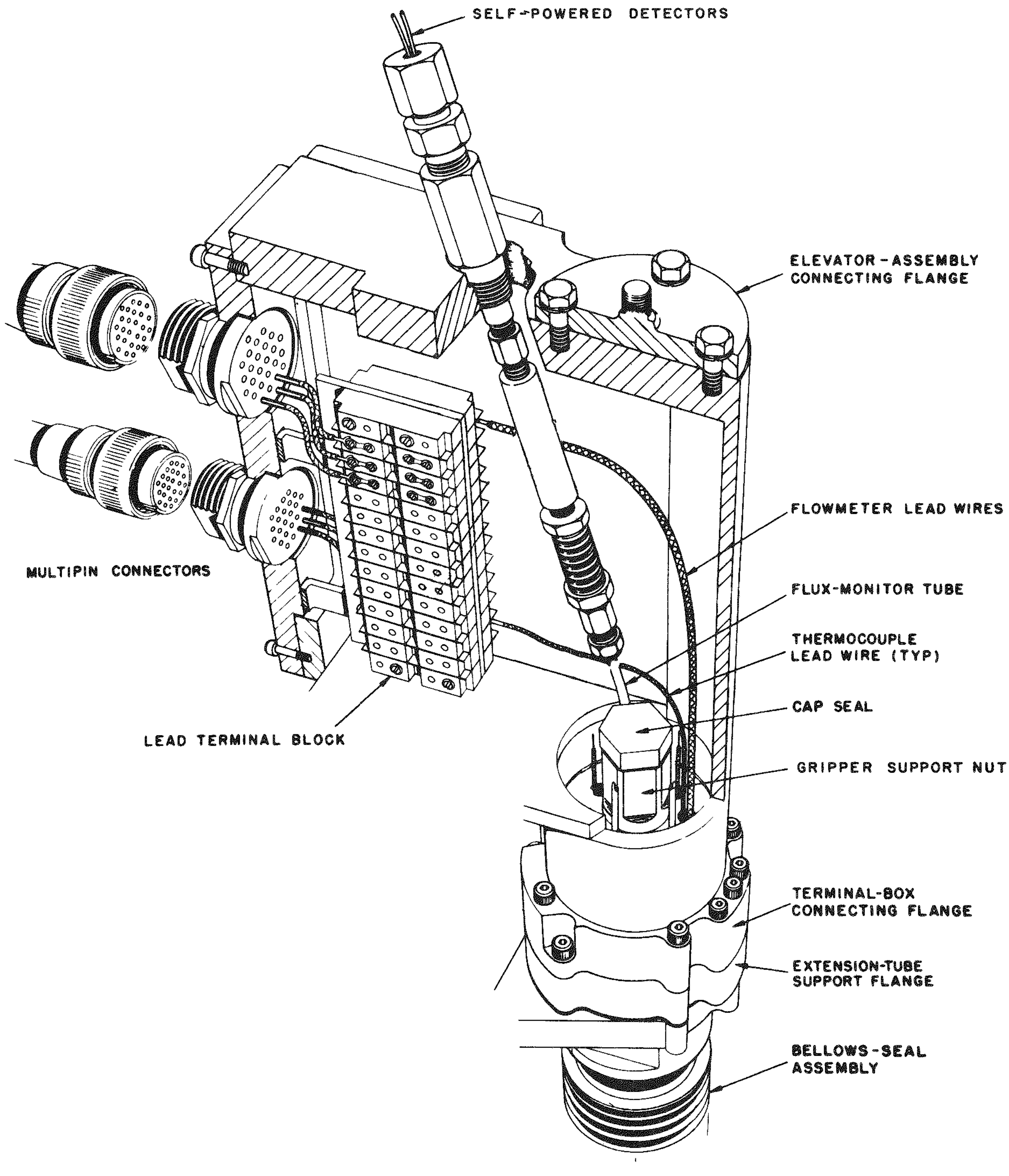


Fig. 4. Terminal Box of XX08

to a terminal block. Connections from the terminal block to the equipment of the EBR-II data-acquisition system (DAS) pass through hermetically sealed multipin connectors in the terminal-box front cover. The box is sealed from the atmosphere as well as from the blanket gas of the reactor. Its bottom is flanged for sealing to the mating flange of the extension tube, and its top is bolted to the flange of the elevator assembly that raises and lowers the instrumented subassembly during fuel handling.

The terminal box and connecting extension-tube drywell are charged with argon gas at 14 psig (92.5 kPa, gauge), a pressure higher than that of the reactor cover gas. Thus, a leak in the extension tube would be indicated by a drop in terminal-box pressure. This pressure is indicated locally, and a pressure-actuated limit switch initiates an alarm if a lower limit of 10 psig (68.9 kPa, gauge) is reached. There is also a high-pressure alarm set at 15 psig (103.4 kPa, gauge).

4. Test Cutting of XX08 Leads

The removal of XX08 from the reactor at the end of its irradiation life will require severing the instrument leads with a double-edged cutting tool driven within a specified torque range. The cutting tool is attached to a 27-ft (8.2-m)-long extension shaft, which is inserted into the subassembly extension tube after the terminal box and gripper assembly are removed. The cutting tool is lowered until it is supported on the subassembly upper adapter. The extension shaft is attached to a cutting drive mechanism, and the instrument leads are cut by rotating the cutting tool 180° while the cutting torque is recorded on a strip chart. This cutoff operation makes it possible to disconnect and separate the extension tube from the subassembly so that the subassembly can be routinely handled for removal from the reactor.

To ascertain that the leads could be readily severed and to obtain a characteristic torque curve of the lead-cutting operation before the actual cutting, an archive test was conducted. The test apparatus was identical to that used for the actual cutting. The lead configuration in the mockup was identical to that in XX08. Figure 5 shows the configuration and the results of the test. The highest torque observed during the test was about 50 lb_f-ft (68 N·m). The results of this test will be used for monitoring the actual lead cutting during removal of the irradiated XX08 from the reactor.

C. Description of Fuel Elements

Subassembly XX08 contains 58 EBR-II Mark-II driver-fuel elements, a number of which were made with jackets of extended length.

1. Fuel Type

The fuel used is a uranium metal-5 wt % fissium alloy. The fuel element is of the Mark-II design, currently used as the reactor driver fuel.

The Mark-II design has a ^{235}U enrichment of 66.8% and a fuel diameter of 0.130 in. (3.30 mm). The cladding OD is 0.174 in. (4.42 mm), and the spacer-wire diameter is 0.049 in. (1.24 mm).

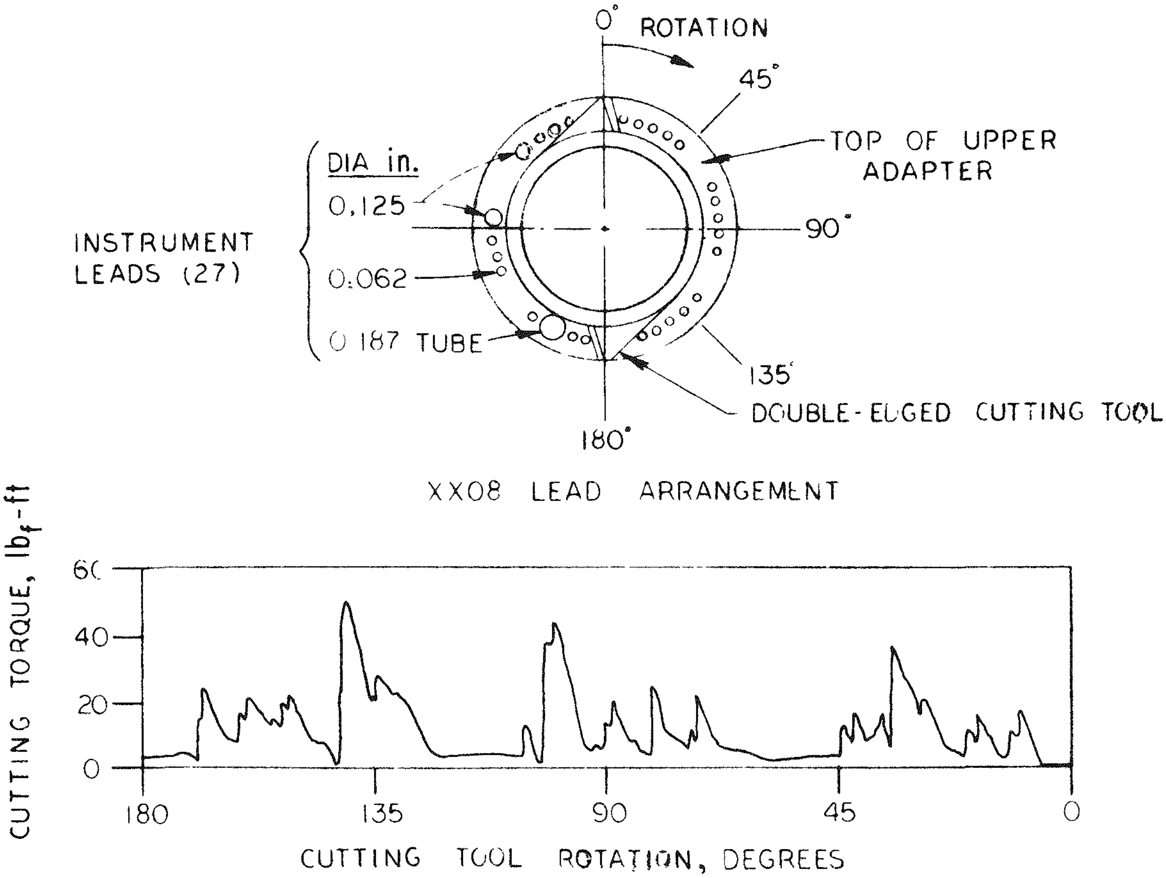


Fig. 5. Arrangement of Instrument Leads in XX08, and Results of Lead-cutting Test. Conversion factors: 1 in. = 25.4 mm; 1 lb_f–ft = 1.365 N·m.

The nominal design parameters for the Mark-II elements in XX08 are listed in Table I. Figure 6, view 1, shows the standard Mark-II design.

2. Modifications for Use in XX08

The 58 fuel elements in XX08 were designed to make maximum use of the existing Mark-II element design. These elements consist of (1) 36 noninstrumented fuel elements identical to the Mark-II design; (2) six noninstrumented fuel elements that had their length extended 2 in. (50.8 mm), but otherwise are identical to the Mark-II design; (3) ten instrumented fuel elements with spacer-wire coolant thermocouples attached, but otherwise identical to the Mark-II design; and (4) six instrumented fuel elements that had their length extended 2 in. (50.8 mm) and have had fuel-centerline thermocouples and spacer-wire coolant thermocouples, but otherwise were similar to the Mark-II design.

TABLE I Nominal Design Parameters for XX08 Fuel Elements

	Standard Mark-II's (46 required)	Extended Mark-II's (6 required)	Mark-II's with Fuel-centerline Thermocouples (6 required)
Location of identification marking	On lower spade	On lower spade	On lower spade
Fuel			
Chemical composition, uranium, wt %	95 ± 1	95 ± 1	95 ± 1
fissium, wt %	5 ± 1	5 ± 1	5 ± 1
Isotopic composition, ^{235}U, wt %	66.72 ± 0.50	66.72 ± 0.50	66.72 ± 0.50
^{234}U + ^{236}U + ^{238}U, wt %	33.28 ± 0.50	33.28 ± 0.50	33.28 ± 0.50
^{234}U + ^{236}U wt %	<1.0	<1.0	<1.0
Form	Cast pin	Cast pin	Cast pin
Density, 10^3 kg/m^3	17.6	17.6	17.6
Length, mm	342.9 ± 0.813	342.9 ± 0.813	342.9 ± 0.813
Diameter, mm	$3.302^{+0.102}_{-0.483}$	$3.302^{+0.102}_{-0.483}$	$3.302^{+0.102}_{-0.483}$
Weight 10^{-3} kg	51.7 ± 1.0	51.7 ± 1.0	51.1 ± 1.0
Cladding (Type 316 solution-annealed stainless steel)			
Inside diameter mm	3.810 ± 0.0127	3.810 ± 0.0127	3.810 ± 0.0127
Thickness mm	0.3048 ± 0.0127	0.3048 ± 0.0127	0.3048 ± 0.0127
Fuel-restrainer (dimple) distance above fuel mm	12.7	12.7	12.7
Fuel-Cladding bond	Sodium	Sodium	Sodium
Level above fuel pin, cold [a] mm (max/min)	38.1/16.9	38.1/16.9	48.2/30.5
Diametral gap, mm	0.508	0.508	0.508
Plenum			
Fill gas	Argon-xenon-helium mixture	Argon-xenon-helium mixture	Xenon-helium mixture
Volume cold [a] mm^3 (max/min)	2573/2327	3152/2906	2527/2369
Plenum/fuel volume ratio cold [a] (max/min)	0.88/0.79	1.07/0.99	0.87/0.82
Volume irradiated to >3 at. % Bu [b] mm^3 (max/min)	1703/1457	2282/2036	1628/1470
Plenum/fuel volume ratio irradiated (max/min)	0.42/0.36	0.56/0.50	0.40/0.36
Axial insulators or reflectors	None	None	None
Element			
Weight 10^{-3} kg	79.7	81.1	82.4
Length, m	0.605	0.656	0.667
Activity at 0.305 m (1 ft) mrem/h			
Gamma	<0.4	<0.4	<0.4
Neutron	<0.2	<0.2	<0.2
Spacer-wire material	Type 316 annealed stainless steel (36 present) Spacer-wire thermocouples (10 present)	Type 316 annealed stainless steel	Spacer-wire thermocouples
Diameter, mm	1.24	1.24	1.24
Pitch m	0.152	0.152	0.152

[a]Preirradiation value at room temperature.

[b]Assumes radial and axial swelling of fuel to cladding and dimples and preirradiation room-temperature volumes for jacket and bond sodium.

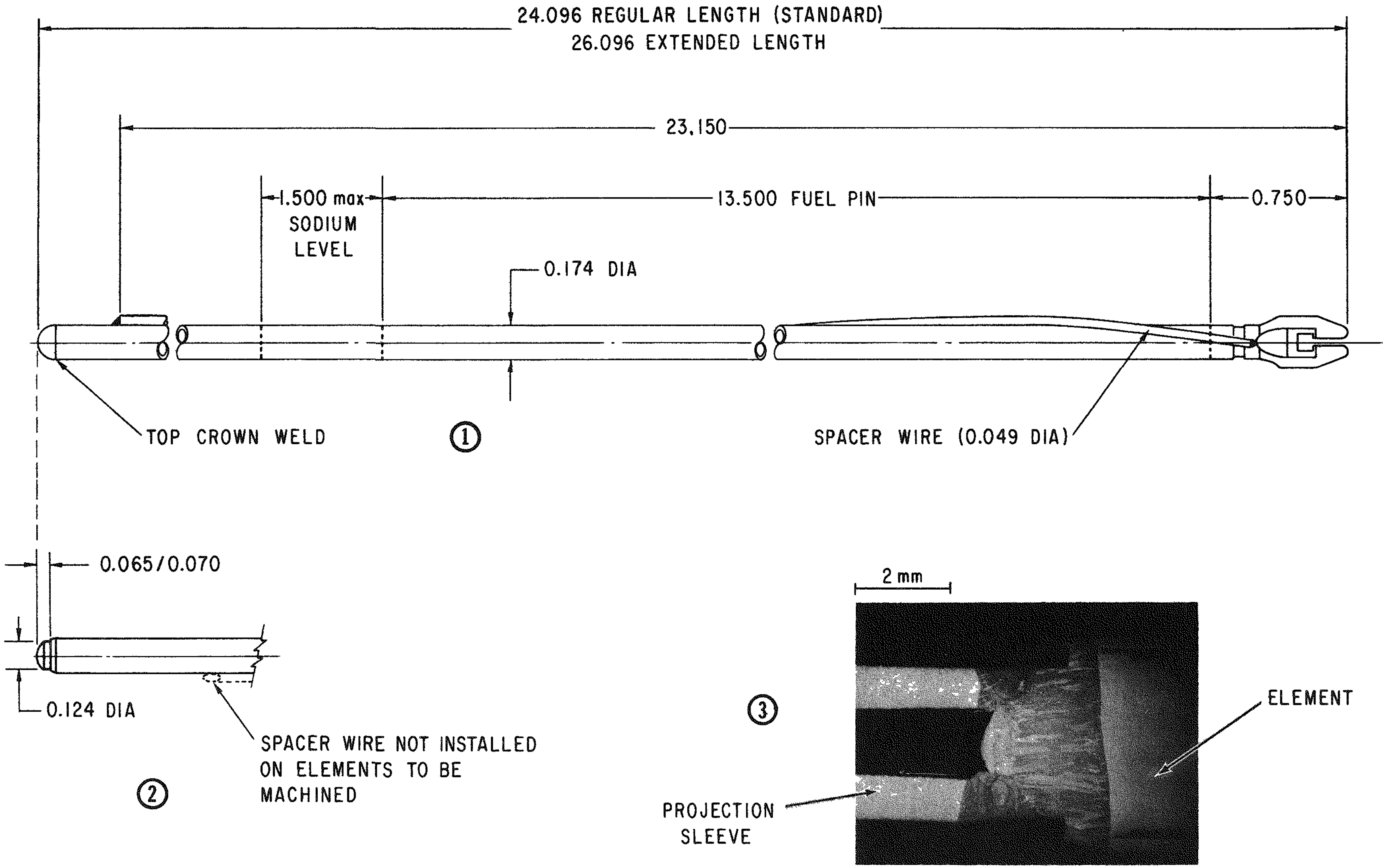


Fig. 6. EBR-II Mark-II Driver-fuel Element and Modifications. 1. Standard Mark-II element (regular and extended length). 2. Crown weld machined for welding of projection sleeve to fuel element (regular length only). 3. Photomicrograph of weld to fuel element. All dimensions in inches; 1 in. = 25.4 mm.

All the fuel elements were manufactured new; that is, none were withdrawn from regular reactor operating inventory. All contained cast fuel pins from the same batch and used cladding of tubing material from the same lot. Other standard components such as tips and plug ends were used from parts inventory as available. All the fuel elements are xenon-tagged.

As-built parameters of each of the elements used in XX08 are presented in Appendix A.

a. Noninstrumented Fuel Elements. The 42 noninstrumented fuel elements consist of 36 Mark-II's of the regular length of 24.096 in. (612 mm) and six Mark-II's of the extended length of 26.096 in. (663 mm). The extended elements are identical to the regular elements, except for their added jacket length of 2 in. (50.8 mm).

Each element is 0.174 in. (4.42 mm) in diameter and has a spacer wire wrapped along its length to a distance of 23.15 in. (588 mm) from the bottom tip. The spacer wire is 0.049 in. (1.24 mm) in diameter and is spiral-wrapped with a 6-in. (152-mm) axial pitch.

Each jacket, plug, tip, and spacer wire is constructed of Type 316 stainless steel.

b. Fuel Elements Instrumented with Spacer-wire Coolant Thermocouples. The 10 fuel elements instrumented with spacer-wire coolant thermocouples are regular-length Mark-II fuel elements without the usual spacer wire. (See Fig. 7.) The element is modified at the top end by machining the top "crown" weld (see Fig. 6, views 2 and 3) to accept a projection sleeve for an extension rod. The rod provides a support surface for brazing the spacer-wire coolant thermocouple to the fuel element at a position other than on the element jacket.

The spacer-wire coolant thermocouple is a 0.049-in. (1.24-mm)-dia wire spirally wrapped on a 6-in. (152-mm) axial pitch on the fuel element. The thermocouple diameter increases to 0.062 in. (1.57 mm) at the extension rod at the top of the element, where the enlarged diameter is accommodated and where the thermocouple is brazed. The bottom end of the thermocouple is extended with 0.049-in. (1.24-mm)-dia solid wire to give enough length for welding to the bottom tip of the element.

The hot junctions of the spacer-wire thermocouples are placed at various axial positions on the 10 fuel elements: two at the bottom of the core; two at 0.4 core height; two at 0.7 core height; three near the top of the core; and one at 1.5 core height. The core height is 13.5 in. (343 mm).

The overall length of the fuel element, including thermocouple extension fittings, is 25.571 in. (650 mm). The overall length of each thermocouple is about 30 ft (9.1 m). The other outside dimensions are the same as those of the regular Mark-II fuel elements described in the preceding paragraphs.

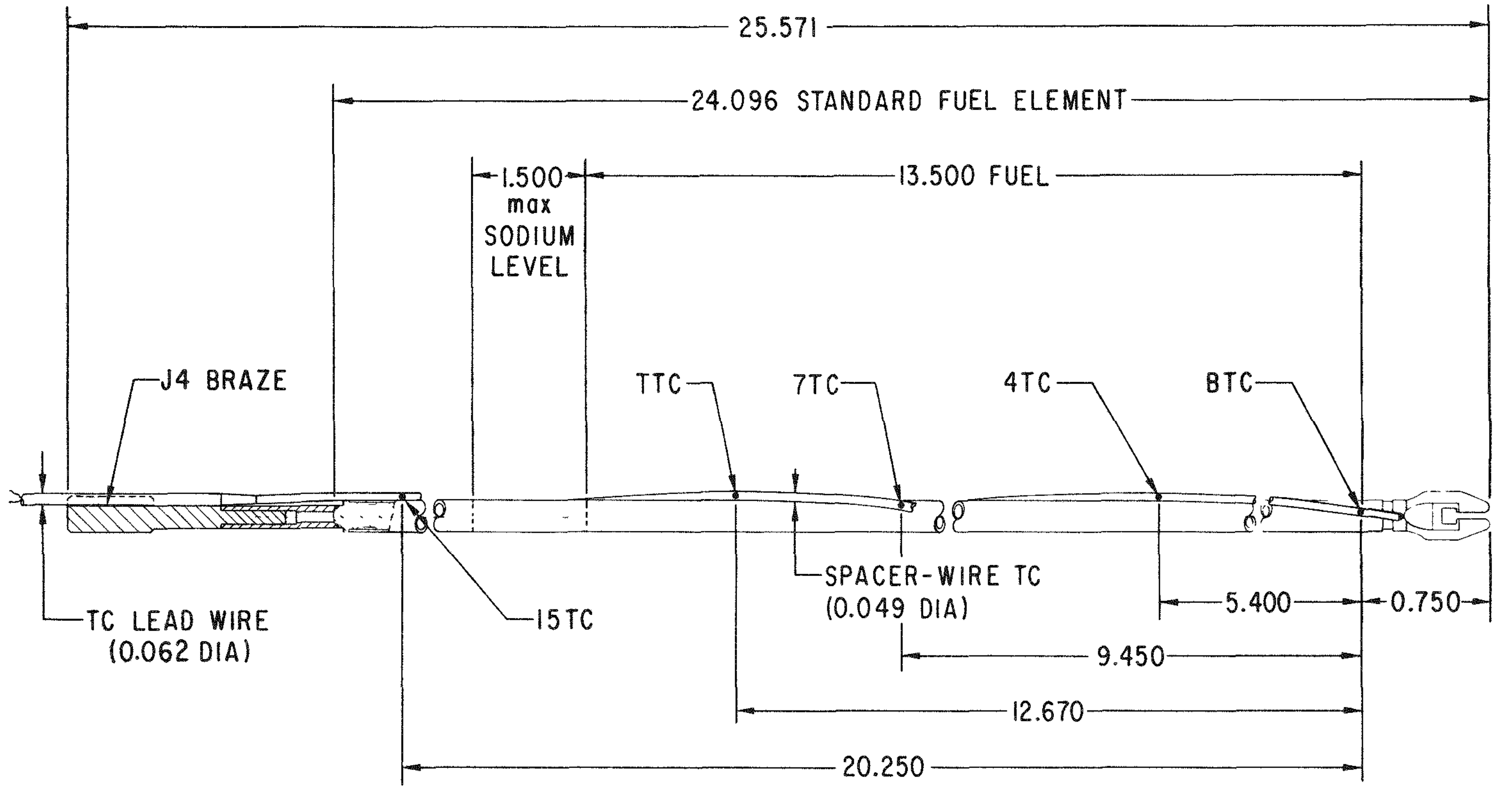


Fig. 7. Detail of XX08 Fuel Element, Showing Location of Spacer-wire Coolant Thermocouples. All dimensions in inches; 1 in. = 25.4 mm. Codes identifying thermocouples--e.g., BTC and 4TC--are explained in Fig. 10 and Table II.

c. Fuel Elements Instrumented with Fuel-centerline Thermocouples and Spacer-wire Coolant Thermocouples. The six fuel elements instrumented with both fuel-centerline thermocouples and spacer-wire coolant thermocouples (see Fig. 8) use an extended-length Mark-II fuel element.

In driver-fuel elements in EBR-II, the peak fuel temperature is at, or near, the top of the fuel. The hot junction of each centerline thermocouple is therefore located near the fuel top so that axial conduction can be minimized while measuring a temperature near the peak value. A hole 0.042 in. (1.07 mm) in diameter and 1.408 in. (35.76 mm) deep is drilled into the top of the fuel pin to accept a 0.029-in. (0.74-mm)-dia thermocouple tip. The thermocouple hot junction is located on the fuel-pin centerline about 0.83 in. (21.1 mm) below the top of the pin. The hole is beveled generously for lead-in of a filler pin that is placed in the thermocouple hole during preassembly (see Fig. 9). As discussed in Sec. IV.B.2, this pin is extracted later in the assembling process to permit entry of the thermocouple through frozen sodium. Three internal dimpled protrusions in the cladding limit the fuel pin to 0.500 in. (12.7 mm) of axial movement.

A top closure cap is welded to the top of the element to serve as a combination cap and coupling. It initially serves as a cap on the fuel-element preassembly (see Fig. 9) after sodium-bonding, and finally as a coupling on the completed fuel assembly. (See Sec. IV.B.2.)

The fuel-centerline thermocouple exits at the top of the fuel element through an adapter, where it is seal-brazed. This adapter, which now serves as the new closure cap of the fuel element, is seal-welded to the top coupling. The adapter also contains a small hole--0.006 in. (0.152 mm) in diameter--that serves as an entry port for the xenon-tagging gas and becomes the final closure-weld seal after tagging.

An extension tube, which slips over the fuel-centerline thermocouple, is welded to the adapter and accommodates the brazing of the spacer-wire coolant thermocouple. The hot junction of this thermocouple is at the same elevation (0.830 in., or 21.1 mm, below the top of the fuel pin) as that of the fuel-centerline thermocouple.

The overall length of the fuel element is 28.249 in. (717.5 mm). The other outside dimensions of the fuel element and of the thermocouple are as previously described at the start of this section (II.C).

D. Instrumentation

1. General Requirements

The basic instrumentation used to meet the XX08 experimental objectives include (a) two calibrated permanent-magnet flowmeters, (b) coolant

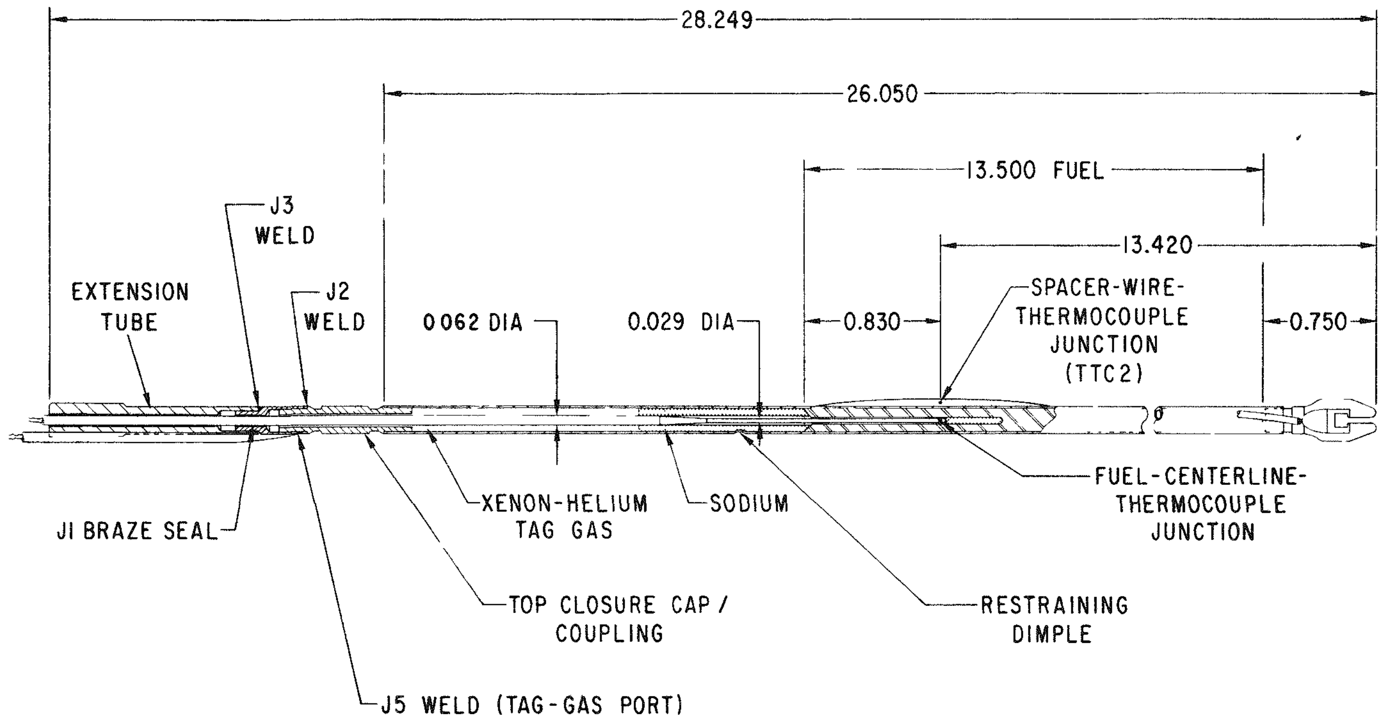


Fig. 8. XX08 Fuel Element with Fuel-centerline Thermocouple and Spacer-wire Coolant Thermocouple. All dimensions in inches; 1 in. = 25.4 mm.

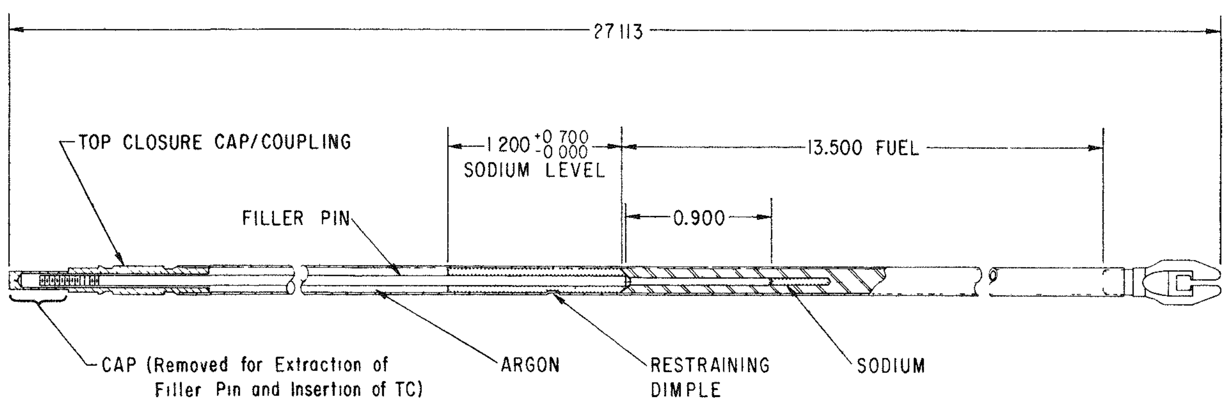


Fig. 9. Preassembly for XX08 Fuel Element with Fuel-centerline Thermocouple. All dimensions in inches; 1 in. = 25.4 mm.

thermocouples at various axial and radial locations, (c) fuel-centerline thermocouples, and (d) two self-powered neutron detectors. Figure 10 shows the layout of the XX08 instrumentation with respect to the fuel elements. In addition to the experimental instrumentation, some supplementary monitoring instrumentation was used. The nonexperimental sensors are described briefly in Sec. II.D.5 below.

The sensors within the subassembly are required to operate reliably at the temperatures and with the accuracies specified in Table II for the duration of the experiment.

2. Thermocouples

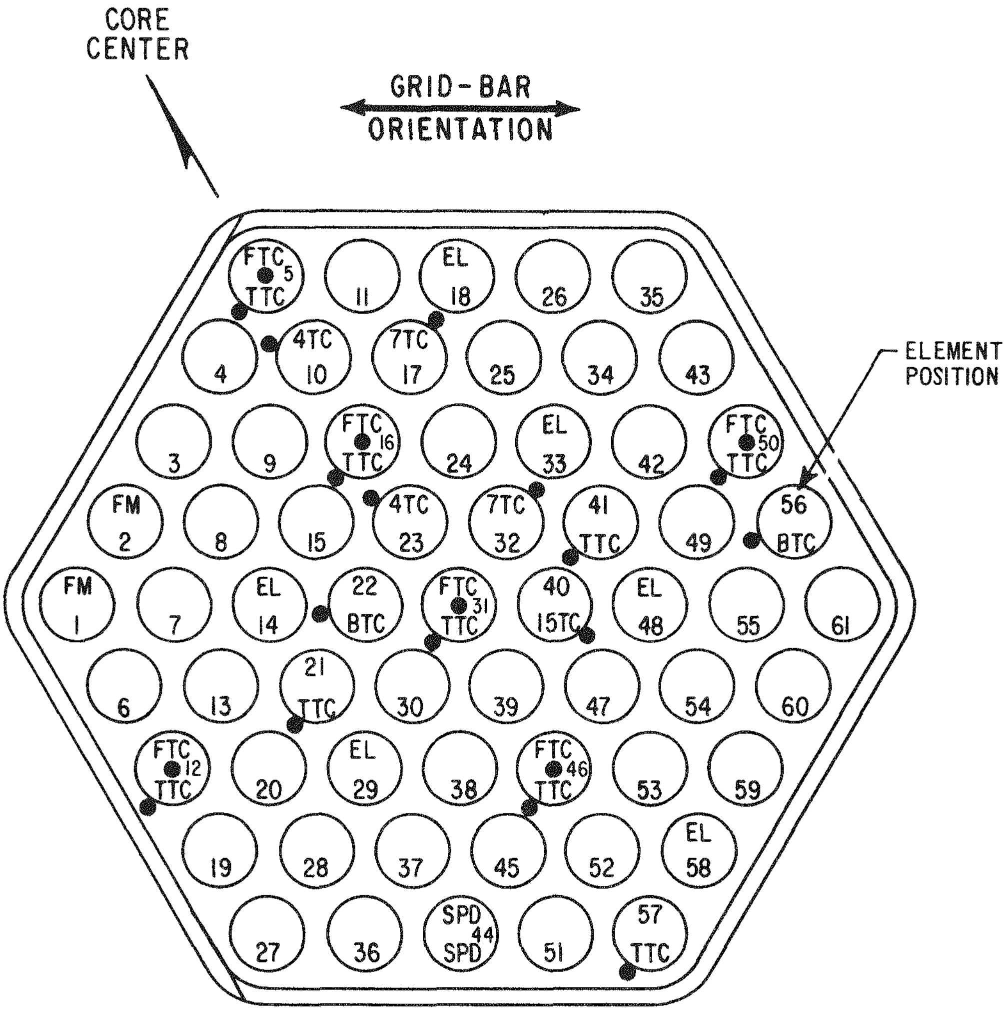
Type K Chromel/Alumel thermocouples were chosen for use throughout XX08. The maximum number of thermocouples that could be used was set by size of the subassembly's upper adapter, which put a limit on the number and diameter of the instrument leads that could be routed out of the subassembly. (The leads of the supplementary instruments in the drywell of the extension tube do not pass through the upper adapter.)

Except for the supplementary terminal-box thermocouple, all thermocouples for XX08 were fabricated to meet the requirements of RDT Standard C 7-6T. This standard specifies stainless-steel-sheathed, magnesium-oxide-insulated Chromel/Alumel thermocouples. The thermocouple-sheath material is Type 316 stainless steel for the spacer-wire coolant thermocouples and Type 304 stainless steel for the outlet-coolant and fuel-centerline thermocouples. Previously fabricated thermocouple cable with Type 304 stainless steel sheath was available in ANL stock and was provided to a vendor for fabrication into thermocouples. Since thermocouple cable with Type 316 stainless steel sheath was not in stock, it was specially fabricated to make the XX08 thermocouples. Three basic thermocouple configurations were needed: fuel-centerline thermocouples, spacer-wire coolant thermocouples, and outlet-coolant thermocouples. The characteristics of each are given below.

a. Fuel-centerline Thermocouples. The fuel-centerline thermocouples are characterized by their 1.6-in. (40.6-mm)-long, 0.029-in. (0.74-mm)-OD hot-junction tip. This reduced-diameter tip provided installation into the fuel pins. A thermal-response time constant of less than 0.060 s was specified, with verification by 100% testing in accordance with the thermal-response-time test specified by RDT Standard C 7-6T.

b. Spacer-wire Coolant Thermocouples. Each spacer-wire coolant thermocouple requires a 0.049-in. (1.24-mm)-OD hot-junction tip. Each thermocouple tip has a length of solid stainless-steel spacer wire butt-welded to it. The length of spacer wire attached is such that when the thermocouple and the attached spacer wire are spirally wrapped on the fuel element, the hot junction will be at the desired reactor-core elevation (bottom of core, 0.4 core, 0.7 core, top of core, and 1.5 core).

c. Outlet-coolant Thermocouples. Each outlet-coolant thermocouple requires a 0.062-in. (1.57-mm)-OD hot-junction tip without attachments.



LEGEND	REQUIRED
FM - FLOWMETER LEAD	2
SPD - SELF POWERED DETECTOR	2
BTC - CORE-BOTTOM COOLANT TC	2
4TC - COOLANT TC 0.137m ABOVE CORE BOTTOM	2
7TC - COOLANT TC 0.240m ABOVE CORE BOTTOM	2
TTC - COOLANT TC TOP OF CORE	9
FTC - FUEL-CENTERLINE TC	6
15TC - COOLANT TC 0.514m ABOVE CORE BOTTOM	1
EL - EXTENDED-LENGTH (0.660m) MK-II ELEMENTS	6

NOTES: a) DOTS REPRESENT LATERAL POSITION OF TC JUNCTIONS IRRESPECTIVE OF AXIAL LOCATION.

b) TWO OUTLET COOLANT TC's (NOT SHOWN) EXIST ABOVE THE FUEL ELEMENTS.

Fig. 10. Layout of Instrumentation in XX08

TABLE II Requirements for XX08 Sensors and Extension Leads[a]

Location in XX08	Number	Sensor Description	Sheath Type	Nominal Size and Type[b]	Standards and Codes	Operating Range (Accuracy)
Subassembly	2	Bottom-of-core coolant TC (BTC)	316 SS[c]	0.062-in -OD, MgO-insulated Chromel/Alumel with 0.049-in. spacer wire	RDT Standard C 7-6T	700-800°F (±1%)
Subassembly	2	0.4-core-height coolant TC (4TC)	316 SS[c]	0 062-in.-OD, MgO-insulated Chromel/Alumel with 0 049-in. spacer wire	RDT Standard C 7-6T	700-900°F (±1%)
Subassembly	2	0.7-core-height coolant TC (7TC)	316 SS[c]	0.062-in.-OD MgO-insulated Chromel/Alumel with 0 049-in spacer wire	RDT Standard C 7-6T	700-1000°F (±1%)
Subassembly	9	Top-of-core coolant TC (TTC)	316 SS[c]	0 062-in -OD MgO-insulated Chromel/Alumel with 0.049-in. spacer wire	RDT Standard C 7-6T	700-1100°F (±1%)
Subassembly	6	Fuel-centerline TC (FTC)	304 SS[c]	0.062-in -OD MgO-insulated Chromel/Alumel with 0 029-in.-OD tip	RDT Standard C 7-6T	700-1200°F (±1%)
Subassembly	1	1 5-core-height coolant TC (15TC)	316 SS[c]	0 062-in.-OD MgO-insulated Chromel/Alumel with 0.049-in spacer wire	RDT Standard C 7-6T	700-1100°F (±1%)
Subassembly	2	Outlet-coolant TC (OTC)	304 SS[c]	0 062-in -OD MgO-insulated Chromel/Alumel	RDT Standard C 7-6T	700-1100°F (±1%)
Subassembly	2	Mark-III permanent-magnet flowmeters	304 SS[c]	0 125-in.-OD, MgO-insulated 304 SS conductors	Spec No ANL-HTI-LMBR-550-G	1-60 gpm (±1%)
Subassembly	2[d]	Self-powered detectors	Inconel sheath in 316 SS conduit	0 062-in.-OD MgO-insulated Inconel 600 conductors	ANL Spec No E0437-0002-SM-00	~10^{15}/cm^2 s (±~20%)
Extension-tube drywell	3	Thermocouples	304 SS[c]	0 062-in -OD MgO-insulated Chromel/Alumel	RDT Standard C 7-6T	70-1100°F (±2%)
Extension-tube drywell	3	Sodium-leak detectors	304 SS[c]	0 062-in -OD MgO-insulated Chromel/Alumel	RDT Standard C 7-6T	>100 kΩ (Not available)
Terminal box	1	Thermocouple	Soft lead	Chromel/Alumel	Manufacturing standard	70-110°F (±2%)

[a]Conversion factors °C (°F - 32)/1 8, 1 gpm 6 31 x 10^{-5} m^3/s, 1 in 25 4 mm

[b]Nominal diameter of leads shall be approximately 0 003 in less than the specified diameter of the portion of the lead located in the bulkhead One exception is the already existing short lead of the AI-002 flowmeter

[c]Leads shall have transition to soft leads at the upper 3 ft (0 9 m) of drywell

[d]Contained in one element tube

3. Flowmeters

The two flowmeters used in XX08 are of the permanent-magnet type similar to that described in Refs. 1 and 3. However, they are of the Mark-III design instead of the earlier Mark-II design described in Ref. 1. The Mark-III flowmeter also was used with good success in instrumented subassembly XX07. The Mark-III design permits the flowmeters to be calibrated in an out-of-pile sodium loop, cleaned, and then installed in an instrumented subassembly for irradiation in EBR-II. The flowmeters, provided by the Components Technology (CT) Division of Argonne National Laboratory, were calibrated simultaneously in a sodium loop. As with test XX07, two flowmeters are installed in XX08 to increase the assurance that at least one will continue to function properly until the test objectives for XX08 are met.

A major objective of the XX08 test program is to obtain information on conditions during flow coastdown and natural convection of the coolant. Because the estimated natural convective flow is about 3% of the full flow value of ~50 gpm (315×10^{-5} m^3/s), both of the two XX08 flowmeters were calibrated over the flow range of ~2-42 gpm (~13-265 x 10^{-5} m^3/s). Appendix B summarizes the flowmeter-calibration report supplied by CT for the two flowmeters used in XX08.

The 1/8-in. (3.18-mm)-dia lead from each flowmeter passes through the active core region of the subassembly inside a conduit tube having the same outside dimensions as the regular fuel elements. This design allowed the flowmeter leads to pass through the core region without changing the hexagonal fuel-element geometry and the normal coolant flow channels in this array.

4. Self-powered Detectors

For direct measurement of the neutron-flux levels, the XX08 instrumentation includes two rhodium (primarily neutron sensitive) self-powered detectors. Reference 4 describes this type of SPD and the experience obtained with it in previous EBR-II instrumented subassemblies. As discussed in the reference, the basis of operation of an SPD is the difference in potential between the detector emitter and its collector that results from the movement of energetic electrons from the former to the latter. This differential electron movement can be measured as either a voltage or a current that is proportional to the rate of neutron or gamma absorption in the emitter.

The SPD's used in XX08 have an OD of 0.062 in. (1.57 mm); the active emitter lengths are 12 and 1 in. (305 and 25.4 mm). The 12-in. emitter is positioned so that its middle coincides with the core-midplane height. The 1-in. emitter is positioned so that its middle is 1/2 in. (12.7 mm) below the top of the core.

Because of the small diameters of the SPD's and the desirability of minimizing the number of nonfueled elements in XX08, a design was conceived that allowed both SPD's to be placed in a single containment tube. This tube is fabricated from the same lot of tubing material used for fuel-element jackets in XX08 (i.e., Type 316 solution-annealed stainless steel).

5. Nonexperimental Sensors

In addition to the primary experimental instrumentation described above, the XX08 vehicle includes supplementary instrumentation intended to monitor the subassembly integrity under various operating conditions. This instrumentation is briefly described in the following paragraphs.

a. Drywell Thermocouples. Three Chromel/Alumel thermocouples are in the drywell region along the extension tube. They are positioned with their hot junctions at elevations of 1, 36, and 227 in. (25.4, 914, and 5766 mm) above the top of the braze bulkhead.

b. Sodium-leak Detectors. Three sodium-leak detectors are in the drywell region along the extension tube. These detectors were fabricated by cutting off the hot-junction end of metal-sheathed Chromel/Alumel thermocouples. If sodium were to leak into the drywell and reach the level of such a detector, electrical continuity would be provided between the otherwise open circuit of the Chromel and Alumel conductors. Therefore, the closed circuit of the thermocouple would serve as an indicator of a sodium leak. Two such detectors are located with a sensing elevation 1 in. (25.4 mm) above the top of the bulkhead; the sensing elevation for the third detector is 36 in. (914 mm) above the bulkhead.

c. Terminal-box Thermocouple. A Chromel/Alumel thermocouple at the connector-receptacle pins just inside the terminal box is used for monitoring temperature at this location.

III. WATER-FLOW TESTS

The XX08 design criteria (see Sec. II.A.1) called for a total subassembly flow rate of 48.9 gpm (309×10^{-5} m^3/s) of 800°F (427°C) sodium. This flow rate is based on a pressure drop of 41.35 psi (285.1 kPa), the design ΔP for a control-rod position in EBR-II.

To improve flow distribution to the fuel-element bundle and to minimize sudden expansion pressure drop, a low-pressure-drop exit section was designed for the upper flowmeter. In addition, a low-pressure-drop flow mixer, located above the fuel-element bundle, was designed to promote coolant mixing for obtaining a mixed-mean outlet coolant temperature. A separate flow test on the flow mixer showed that the pressure drop across it was 2.6 psi at 48.9 gpm (18 kPa at 309×10^{-5} m^3/s).

The inlet-flow-hole sizes were determined from a series of water-flow tests made with a full-scale mockup of XX08 (see Appendix C). A full-scale mockup was used so that the experimentally determined flow-versus-pressure-drop characteristics would be exactly the same as those for the actual XX08; no extrapolations or calculations were necessary.

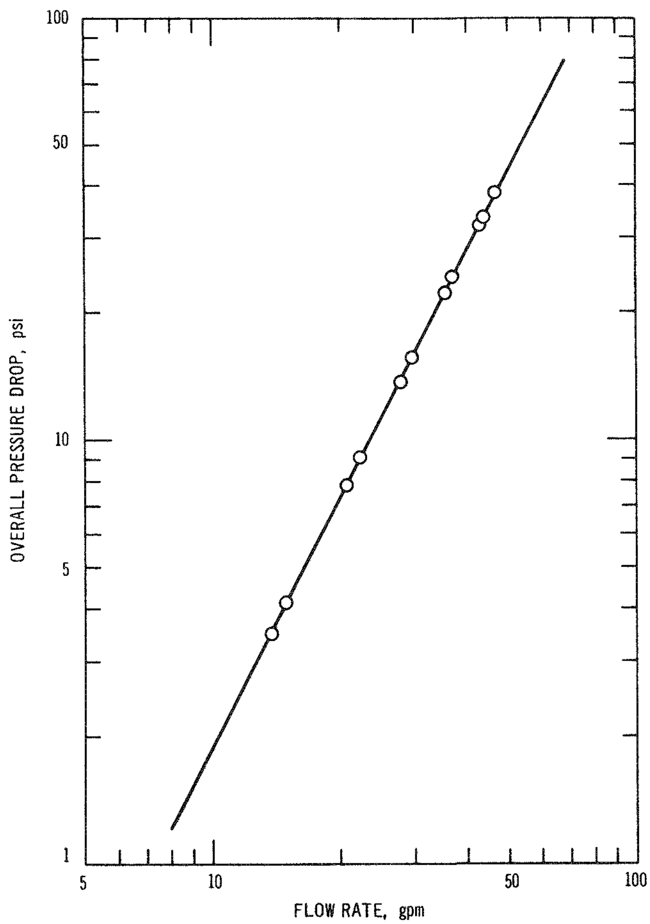


Fig. 11. Flow Rate vs Pressure Drop for XX08. Fluid is sodium at 800°F (427°C). Conversion factors: 1 psi = 6.9 kPa; 1 gpm = 6.3×10^{-5} m^3/s.

The final relationship between pressure drop and flow rate for XX08 is shown in Fig. 11. The sodium data points shown were derived from the water-flow tests. The water temperature was measured at each data point, and the water density and viscosity values at those temperatures were used. The water data were converted to the equivalent 800°F (427°C) sodium data by the following conversion factors:

$$Q_{Na} = F_Q \times Q_w \text{ (gpm)}$$

and

$$\Delta P_{Na} = F_{\Delta P} \times \Delta P_w \text{ (psi)},$$

where

$$F_Q = \frac{\rho_w}{\rho_{Na}} \frac{\mu_{Na}}{\mu_w}$$

and

$$F_{\Delta P} = \frac{\rho_w}{\rho_{Na}} \left(\frac{\rho_{Na}}{\rho_w}\right)^2.$$

The inlet-flow holes in the lower adapter, as determined by the flow tests, consist of three 0.250-in (6.35-mm)-dia holes and three 0.347-in. (8.81-mm)-dia holes. All of these six holes are at the same elevation, with the large holes and small holes alternated. The equivalent sodium flow rate in the initial test with these holes was 48.9 gpm (309×10^{-5} m^3/s) at a pressure drop of 41.35 psi (285.1 kPa). A test done to determine the reproducibility of the results yielded a flow rate of 48.7 gpm (307×10^{-5} m^3/s).

IV. FINAL ASSEMBLING OF XX08

Final assembling of XX08 includes procurement of the individual components, assembling of the fuel elements, and assembling of the complete experimental vehicle. Included in the last category are the instrument splices that connected the in-core sensors to the terminal box and ultimately to the EBR-II data-acquisition system (DAS). These various phases of final assembling are discussed below.

A. Procurement of Components

Many of the components for XX08 (e.g., the upper and lower adapters, the hexagonal can, and the extension tube) were fabricated in the ANL-East Central Shops in accordance with the appropriate design criteria, procedures, and quality-assurance requirements. These components were procured in generally the same manner for XX08 as for previous instrumented subassemblies. The two permanent-magnet, Mark-III flowmeters were supplied by the Components Technology Division of ANL. The upper flowmeter was shortened to accommodate a flow diffuser downstream of the flowmeter. Also, an additional set of electrodes was incorporated for possible use of a time-of-transit technique of flow measurement. The rhodium self-powered detectors were procured from a commercial vendor (Reuter-Stokes of Canada).

The thermocouples were obtained from two commercial vendors. The fuel-centerline and outlet-coolant thermocouples were fabricated from stock material obtained from the ORNL Large Scale Procurement of Temperature Sensors (LSPTS) program. The spacer-wire coolant thermocouples were newly fabricated from vendor's stock, because suitable Type 316 stainless-steel sheath material was unavailable from LSPTS. The thermocouples were tested for conformance to specification requirements. Such testing included helium leak testing to verify sheath integrity, testing of thermal response time, and testing to verify calibration accuracy at elevated temperatures simulating reactor conditions.

B. Assembling of Elements

Making the fuel-element assemblies first required acquisition of EBR-II Mark-II driver-fuel elements, several new hardware components, and instrumentation components. All 58 of these elements were manufactured by the ANL-West Fuels Manufacturing Facility in accordance with the appropriate procedures and quality-assurance requirements. Of these 58 elements, 42 were used as manufactured and 16 were subsequently modified at ANL-East to include instrumentation before use in XX08. (See Sec. II.C.2 for a description of the 58 fuel elements.) The 16 elements requiring addition of instrumentation were the 10 with spacer-wire coolant thermocouples and the six with fuel-centerline thermocouples and spacer-wire coolant thermocouples. These elements required different fabrication and assembling techniques, described in detail in the following sections.

1. Elements with Spacer-wire Coolant Thermocouples

The 10 fuel elements with spacer-wire coolant thermocouples only were made from Mark-II elements that had been produced without the spacer-wire wrap. These elements were modified for use in XX08 in the following manner:

a. The previously welded top end closure was machined to a special weld-joint configuration as shown in Fig. 6, views 2 and 3.

b. A 0.125-in. (3.18-mm)-dia, 0.625-in. (15.88-mm)-long tubular projection for the extension was assembled to the machined end and welded in place by an orbital-arc TIG (tungsten electrode/inert gas) welding process.

c. A 1.387-in. (35.23-mm)-long extension rod machined with a spiral groove to accommodate the spacer-wire thermocouple at the upper end was made available for attachment to the fuel element at the location of the tubular-sleeve projection.

d. A spacer-wire thermocouple was attached to the bottom tip of the element by manual TIG welding and then spirally wrapped at a 6-in. (152-mm) pitch up to the original fuel-element end.

e. The extension rod described in step c above was then assembled to the tubular projection and oriented to accept the continuing spirally wrapped thermocouple.

f. This assembly was then clamped in place, and the extension rod was tack-welded to the tubular projection.

g. The thermocouple was then brazed to the extension rod, and the clamp was removed.

Figure 7 shows the completed assembly of the fuel element and the spacer-wire coolant thermocouple.

2. Elements with Fuel-centerline and Spacer-wire Thermocouples

The six fuel elements fitted with both fuel-centerline thermocouples and spacer-wire coolant thermocouples were manufactured and specially preassembled (see Fig. 9) at ANL-West with special hardware components. With this kind of preassembling, mostly standard methods and techniques could be used for cold-line assembly at ANL-West. Moreover, the thermocouple assemblies could be readily added at ANL-East without affecting the basic cladding and its closure welds. This thermocouple-assembling work included processes such as sodium filling, xenon tagging, element closure welding, and sodium bonding of fuel and thermocouple. Because specialized techniques and procedures were developed for production of these elements, each phase of the fabrication and assembly is described in detail in the following sections.

a. Preassembly Fabrication. The fuel pins for these elements were obtained from ANL-West, where they were made and then shipped to ANL-East for further processing. At ANL-East, a hole, nominally 0.042 in. (1.07 mm) in diameter and 1.312 in. (33.32 mm) deep, was made by electrical-discharge machining into one end of each pin. The pins were then returned to ANL-West for preassembling, sodium loading, and closure welding.

It was desirable to use the normal, approved procedures and techniques for the sodium bonding of these elements. However, the great length of the thermocouples would have precluded the use of existing equipment. Therefore, the thermocouples were not assembled at this time, and the preassembly concept (see Fig. 9) was used. The elements, after the proper amount of sodium had been added to them, were sealed with a special intermediate top cap that was welded to the element tube by the orbital TIG process. This special closure cap provided for the inclusion of a carbon-steel filler pin that extended to the bottom of the thermocouple hole in the fuel pin. Use of the special closure cap and the filler pin allowed these elements to be processed through sodium bonding, bond inspection, and radiography along with regular production-line Mark-II elements. Acceptable elements were then shipped to ANL-East for final assembling.

b. Final Assembling. As noted above, the sodium-bonded fuel-element preassemblies with the special closure caps were sent to ANL-East for final assembling of the completed element. Figure 9 shows the details of the fuel-element preassembly, with the filler pin, the fuel pin, and the top closure cap in place. The thin-wall tubular extension on the top of the closure cap was designed to be easily filed away to expose the threaded top end of the filler pin. The filler pin was then removed in a welding chamber filled with an inert 70% helium-30% argon-gas mixture. The space occupied by the filler pin in the sodium and fuel pin was then available for the insertion of the actual fuel-centerline thermocouple.

The thermocouple was coupled to the fuel element as a preassembly consisting of (a) the thermocouple brazed to an adapter sleeve 0.470 in. (11.94 mm) long and (b) an extension sleeve that was loosely strung over the thermocouple sheath above the adapter sleeve. (See Fig. 12.) In this preassembly, the extension tube is a heavy-wall tube 1.387 in. (35.23 mm) long and with an ID large enough to accommodate the 0.062-in. (1.57-mm)-dia fuel-centerline thermocouple, which passes through its center. A spiral groove is machined on its OD at a 6-in. (152.4-mm) pitch to accommodate the spacer-wire coolant thermocouple.

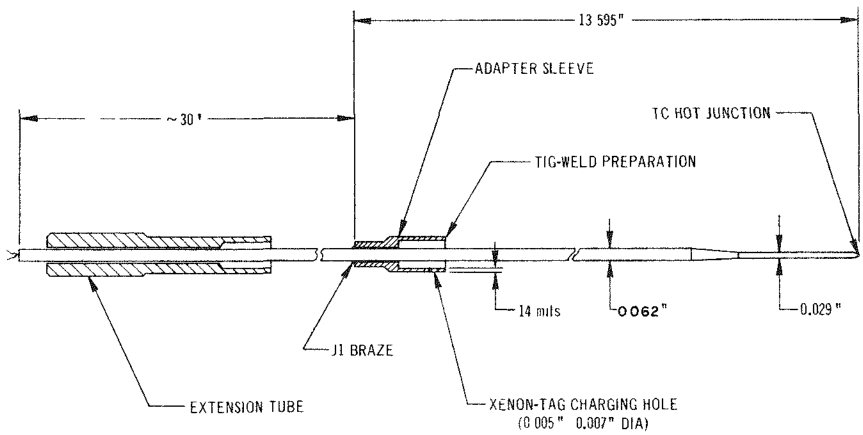


Fig. 12. Thermocouple Preassembly for Fuel Elements Containing Fuel-centerline Thermocouples. Conversion factors: 1 in. = 25.4 mm; 1 ft = 0.3048 m; 1 mil = 2.54×10^{-2} mm.

The thermocouple preassembly was constructed by first assembling the extension sleeve over the thermocouple and then brazing the thermocouple to the adapter sleeve at J1. The length of the emergent thermocouple was carefully established before brazing. Figure 13 (top view) shows a longitudinal cross section through the J1 braze and is typical of the metallurgical structure observed in a development sample. Figure 13 (bottom view) is an enlarged view of the ends of this braze. The excellent braze flow and minimum reaction with the thin [8-mil (0.2-mm)-wall] stainless-steel thermocouple sheath can be seen in this view.

After the J1 braze was completed, the thermocouple preassembly was assembled with the fuel-centerline-thermocouple fuel element as shown in Fig. 8. The J2 weld joined the preassembly to the fuel element. It was made with an orbital-arc TIG process in the welding chamber shown in Fig. 14. This chamber, which has glove ports in the door, can be evacuated and filled with the welding-arc cover gas.

To complete the assembly of the two preassemblies, the thermocouple preassembly was fitted through a vacuum seal on the top of the welding chamber and pushed downward directly above a stationary three-jaw chuck.

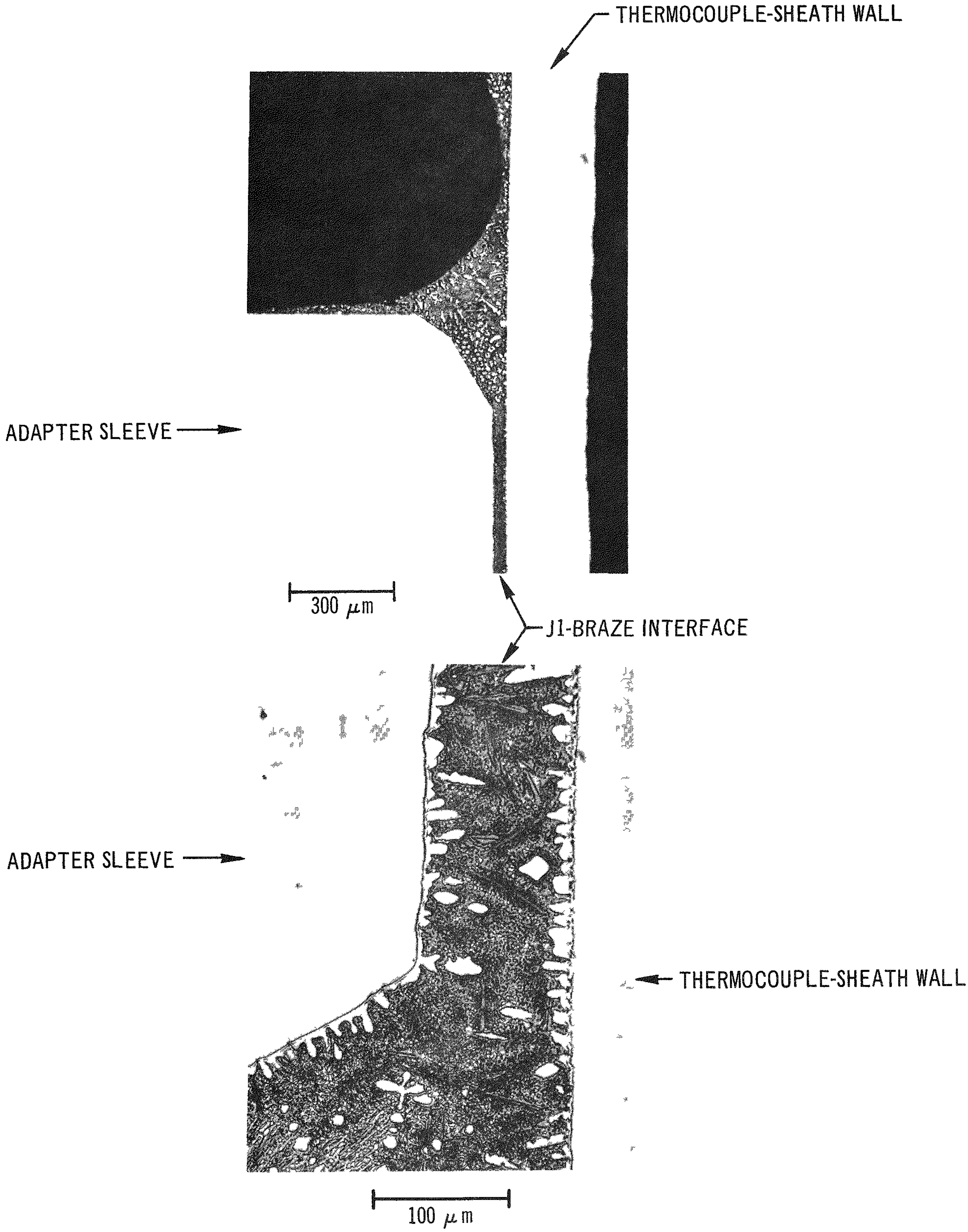


Fig. 13. Longitudinal Cross Sections through J1 Braze of Thermocouple Preassembly

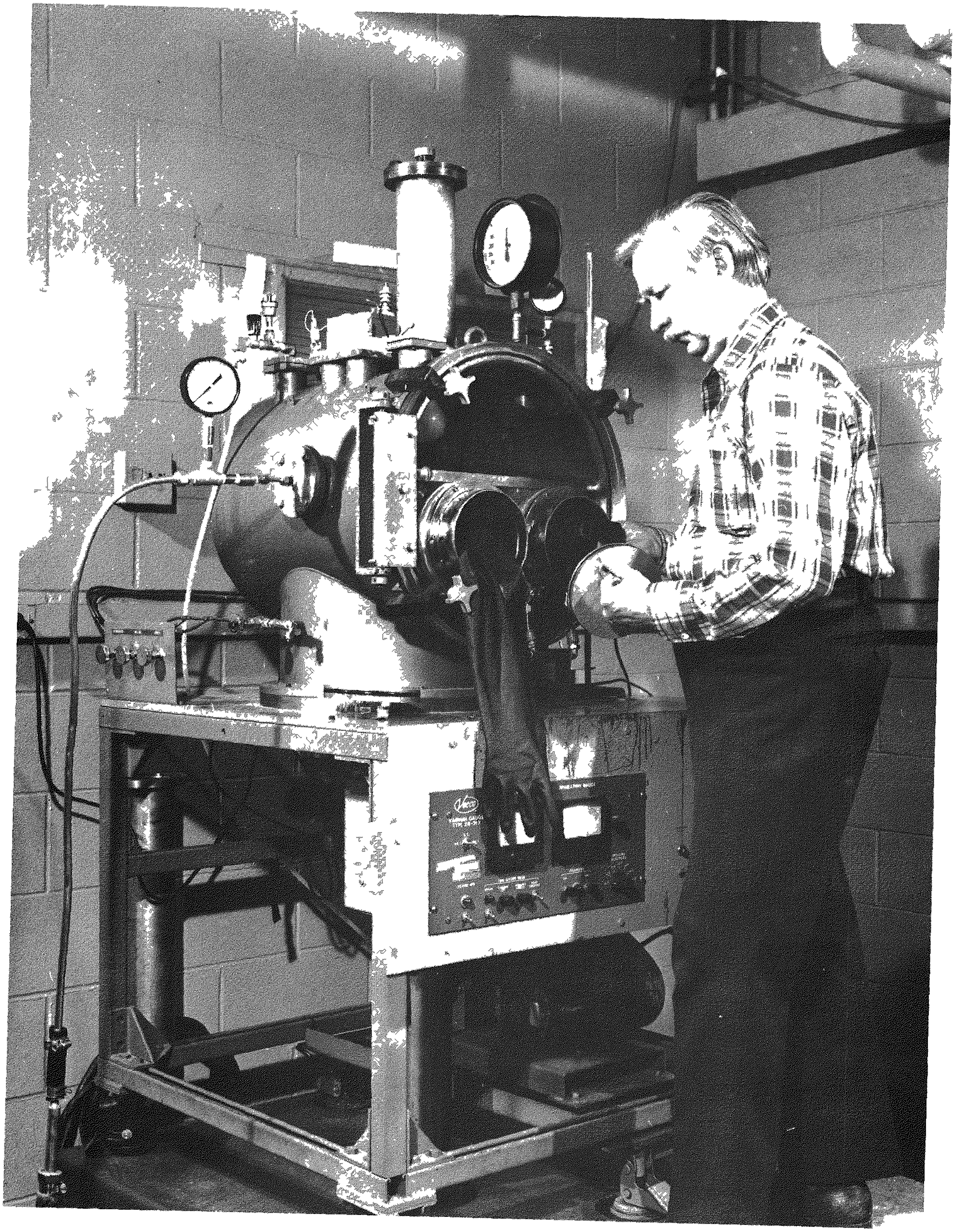


Fig. 14. Controlled-atmosphere Welding Chamber in Which a Fuel-centerline-thermocouple Preassembly Was Joined to a Fuel Element. ANL Neg. No. 104-77-99

The remaining external length of sheathed thermocouple was coiled and attached to a perforated hardboard. The board was also used as a convenient, protective carrier for the finished fuel element, which, along with its integral thermocouple, was attached to the board after being welded and removed from the welding chamber.

The fuel-element preassembly containing the filler pin and the expendable tip was fitted with a tubular gauging fixture designed to position the weld interface so that it was lined up with the tungsten electrode in the orbital-arc welding head. This fixture set the distance from the surface of the J2 weld preparation on the intermediate top cap to the top of the stationary three-jaw chuck. The fuel-element preassembly and attached gauge were then placed in the three-jaw chuck in the welding chamber, as shown in Fig. 15. The expendable tip is shown protruding above the fixture, ready to be filed away to expose the threaded top end of the filler pin (thermocouple facsimile).

Before the filing was done, however, the preassembly and fixture were lowered and secured in the stationary three-jaw chuck, as shown in Fig. 16. In this position, the gauge supported the element preassembly and protected it from damage. When the expendable tip was removed, the threaded end of the filler pin was exposed and was ready for withdrawal. Figure 17 shows the exposed end of the filler pin protruding above the gauge fixture after the tip has been filed away. Figure 18 shows the filler pin partially removed by the pin-puller attachment.

Figure 19 shows the fuel-element preassembly with its top open and the filler pin removed. In addition, the tubular gauging fixture has been removed and replaced with a split-block fixture. This exchange was necessary to expose the J2 weld preparation on the intermediate top cap while the gauged distance set by the tubular fixture was retained. A split-type fixture was used because it could be removed easily. Before the tubular fixture was removed, three closely sized reamers were manually rotated through the thermocouple access hole in the intermediate top cap. This was done to remove as much as possible of the bond sodium that may have been transferred into the annulus between the filler pin and the intermediate top cap during the earlier bonding operation at ANL-West. With the split-block fixture in place, the fuel element could be loosened from the three-jaw chuck and manipulated as necessary to facilitate inserting the fuel-centerline thermocouple into the element.

When the thermocouple had been properly installed and the J2-weld interface established, the assembly was again secured in the three-jaw chuck at a location dictated by the fixture. At this time, the fixture was removed, and the orbital-arc welding head was installed. Figure 20 shows the fuel element and thermocouple assembly in the welding head, its position set by the welding-head positioner. Copper chills (indicated in Fig. 15) were added to the bottom clamps on the welding head to prevent the temperature of the intermediate top cap from rising above the melting point of sodium.

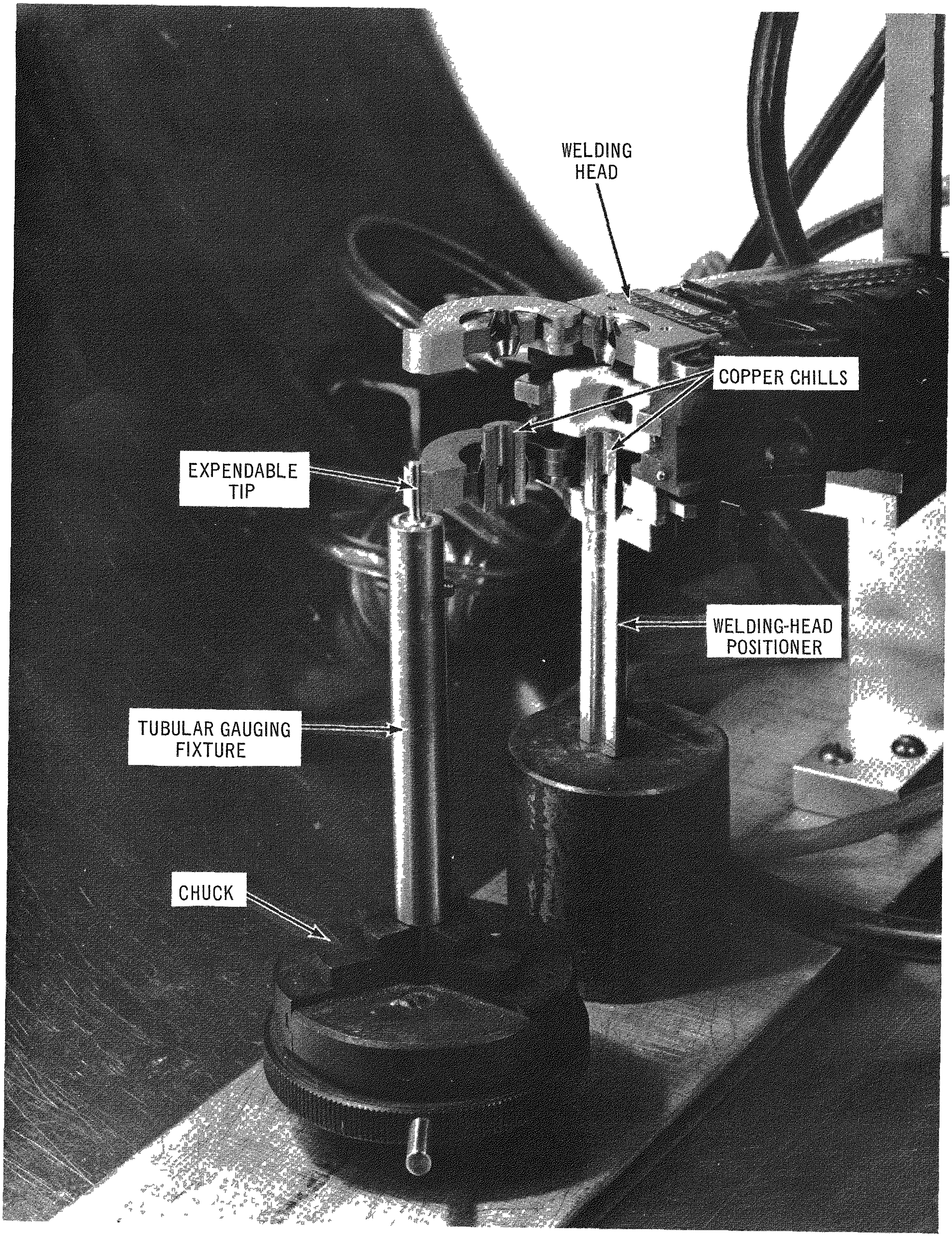


Fig. 15. Fuel-element Preassembly and Surrounding Gauging Fixture Placed in Three-way Chuck (Foreground) in Welding Chamber. ANL Neg. No. 104-77-100.

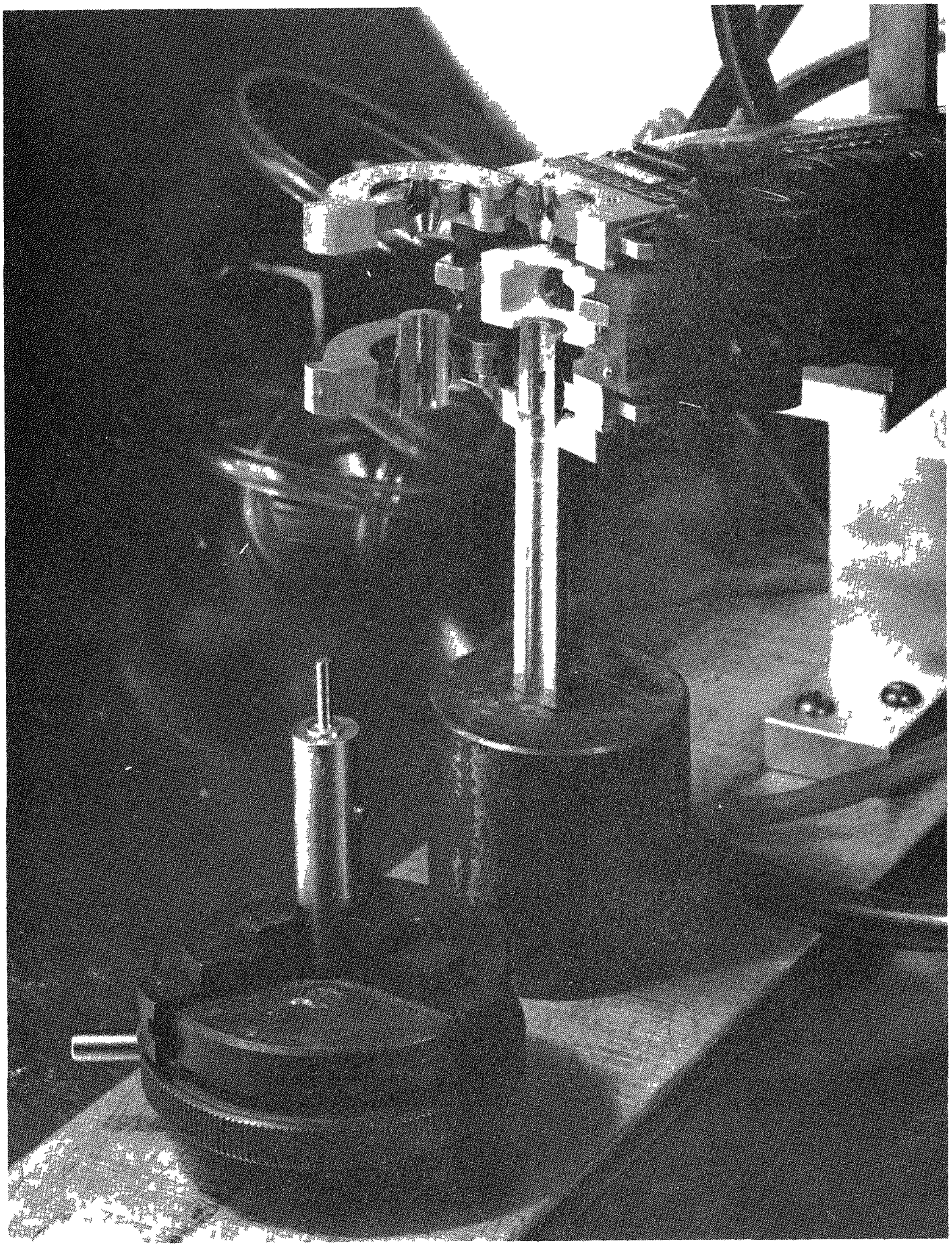


Fig. 16 Element Preassembly and Fixture Lowered in Chuck before Expendable Tip Is Filed Off. ANL Neg. No. 104-77-101.

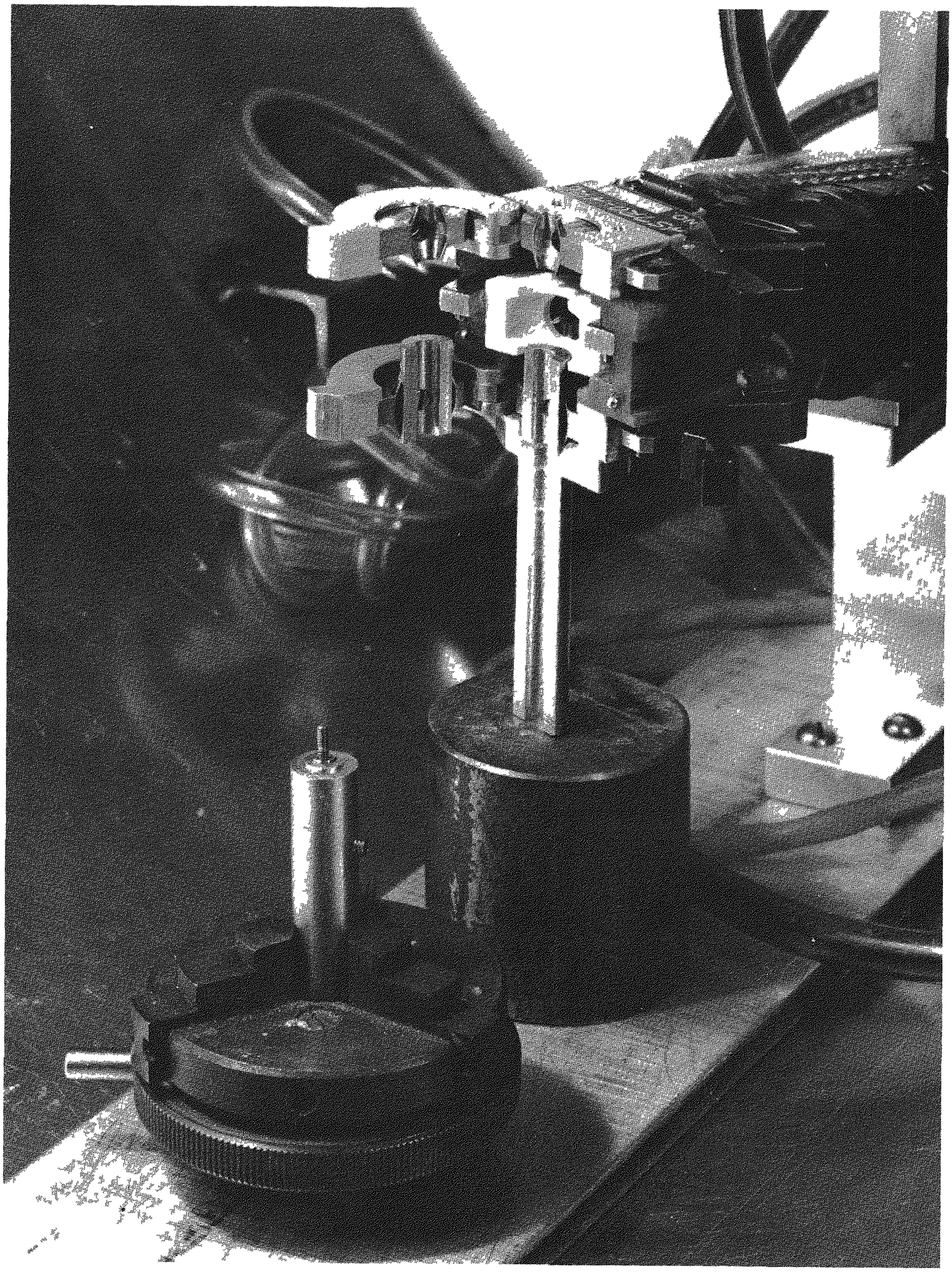


Fig. 17. View after Filing Off Expendable Tip to Expose Threaded End of Filler Pin of Element Preassembly. ANL Neg. No 104-77-103.

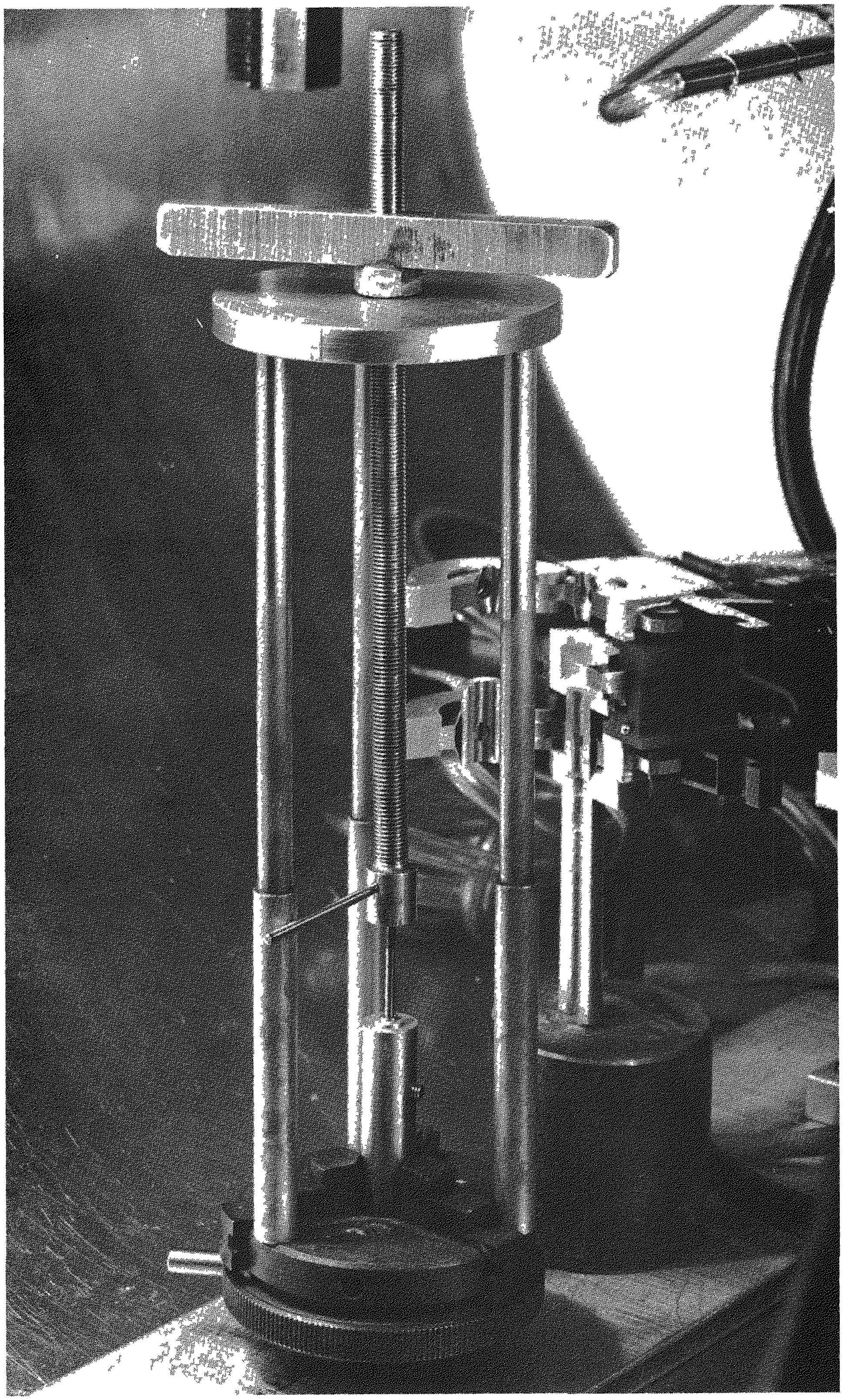


Fig. 18. Filler Pin Being Pulled from Fuel-element Preassembly. ANL Neg. No. 104-77-107.

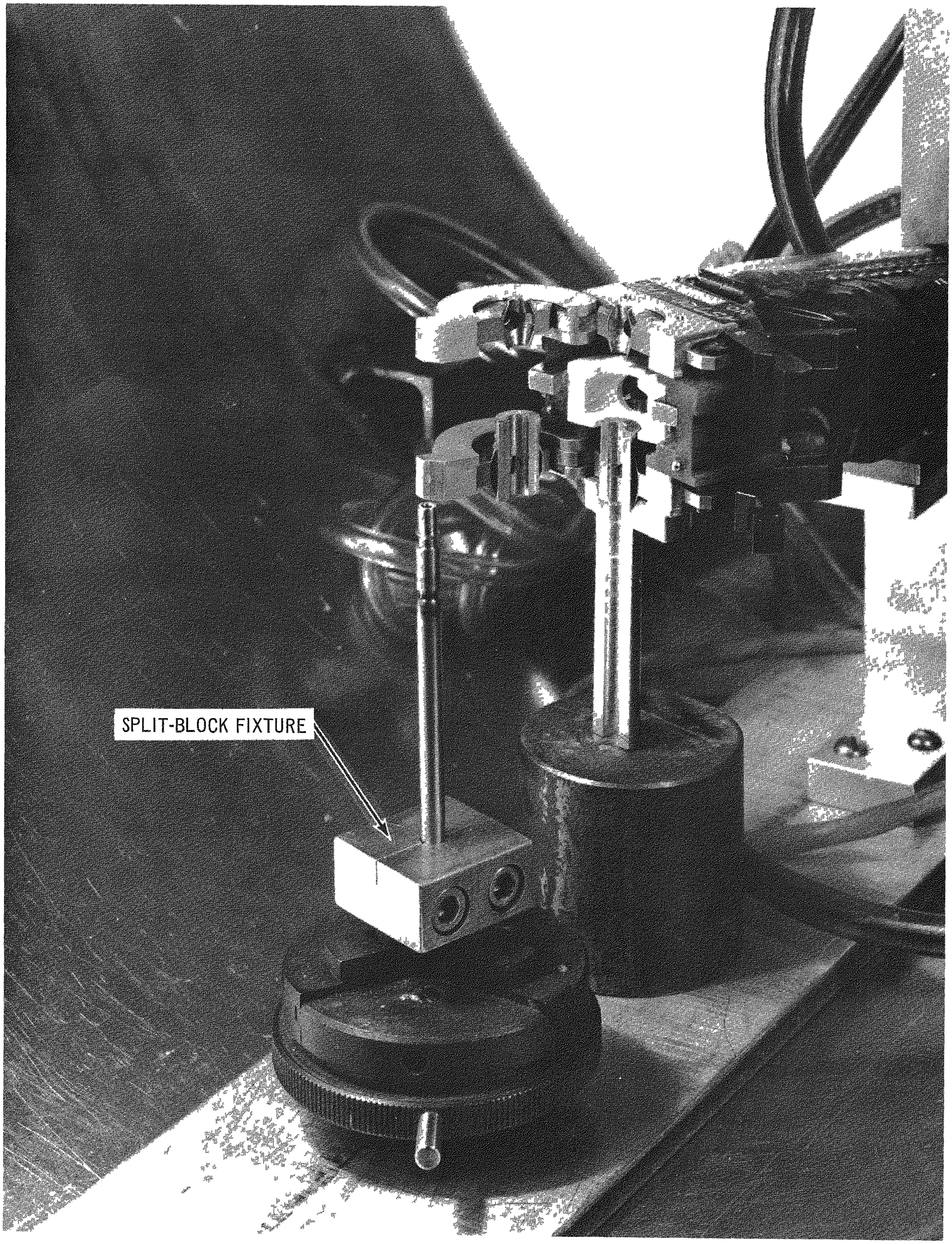


Fig. 19. Element Preassembly after Filler Pin Has Been Removed and Tubular Gauging Fixture Replaced with Split-block Fixture. ANL Neg. No. 104-77-106.

Fig. 20. Fuel-element and Thermocouple Preassemblies Positioned in Welding Head. ANL Neg. No. 104-77-105.

Without the chills, sodium in contact with the bottom of the top cap and the thermocouple would melt and be forced out through the annulus by the expanding gas in the fuel-element plenum. This sodium migration is not detrimental to the TIG closure weld at J2, but could have caused trouble when the final laser closure of the xenon-gas access hole was made. (See next section.) During TIG welding, the temperature in this area was about 150°C without chills. The addition of the chills lowered the temperature in the area to 65°C.

c. Xenon Tagging. For the XX07 assembly,[2] the fuel-centerline-thermocouple elements were xenon-tagged before inserting the thermocouple preassembly and making the J2 final-closure TIG weld. For XX08, the xenon tag gas was introduced after inserting the thermocouple preassembly and making the J2 TIG weld. The tag gas was introduced through a 0.006-in. (0.152-mm)-dia hole in the wall of the adapter sleeve. The final closure weld of the hole was made by laser welding.

After the preassemblies were TIG-welded, the completed element, with thermocouple in place, was transferred to the xenon-tagging chamber shown in Fig. 21. The laser welder is also shown in this figure. The tagging chamber, equipped to evacuate the element plenum and backfill with helium and xenon, had a quartz window for viewing the fuel element in the area of the top cap. The laser beam was focused by observing the xenon charging hole in the adapter sleeve through the quartz window. Inside the chamber, the fuel-element plenum was evacuated to a pressure of about 25 μm of mercury (3.333 kPa). The unique mixture of xenon isotopes was backfilled to a pressure of 0.5 atm (51 kPa). The xenon was followed by helium until the element-plenum pressure returned to 1.0 atm (101 kPa), at which time the laser weld was made to close the charging hole.

Trouble was encountered in making the laser closure weld, because the weld-preparation design was simply a hole in the wall of a tube. With this type of design, the weld metal during laser welding is held firmly on all sides by the tube wall not heated by the laser beam. Upon cooling, cracks develop along the long, columnar grain boundaries, particularly those 45-90° to the direction of the tensile cooling stresses. An etched transverse cross section (Fig. 22) through a laser closure weld in the Type 316 stainless steel tube of the element top cap revealed a large intergranular crack typical of those experienced in this weldment. This condition could not be eliminated without changing either the design of the weld joint or the type of material to one of a ferrite-controlled composition. Neither alternative could be used at the time. Therefore, the final closure of the xenon charging hole was produced in two steps. After the laser weld, a fusion overlay was applied by the orbital-electrode TIG welder, starting 90° before the laser weld and stopping 90° beyond it. This procedure provided crack-free welds meeting all the requirements for leak tightness and wall thickness.

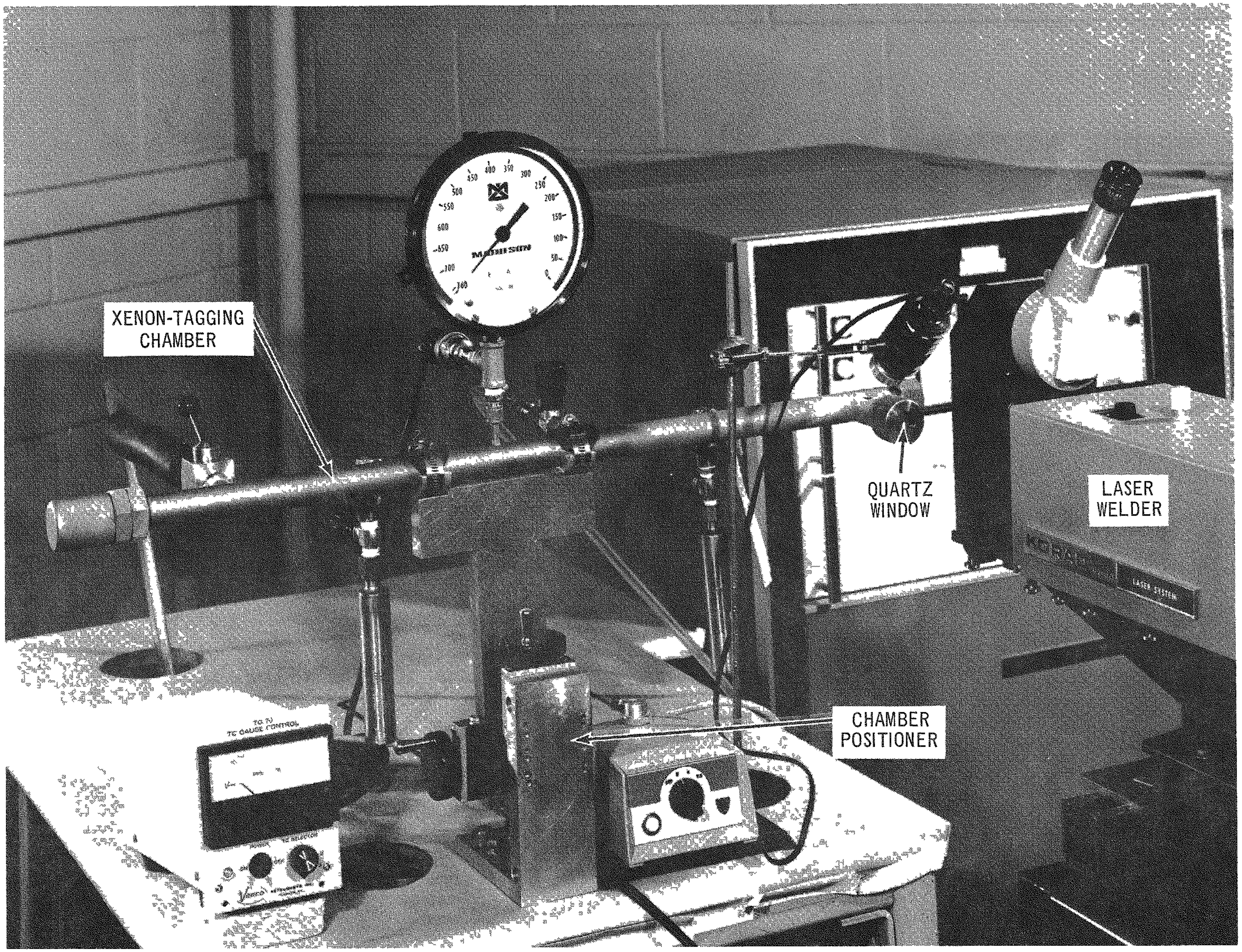


Fig. 21. Apparatus for Xenon-tagging Fuel Elements for XX08. ANL Neg. No. 104-76-299.

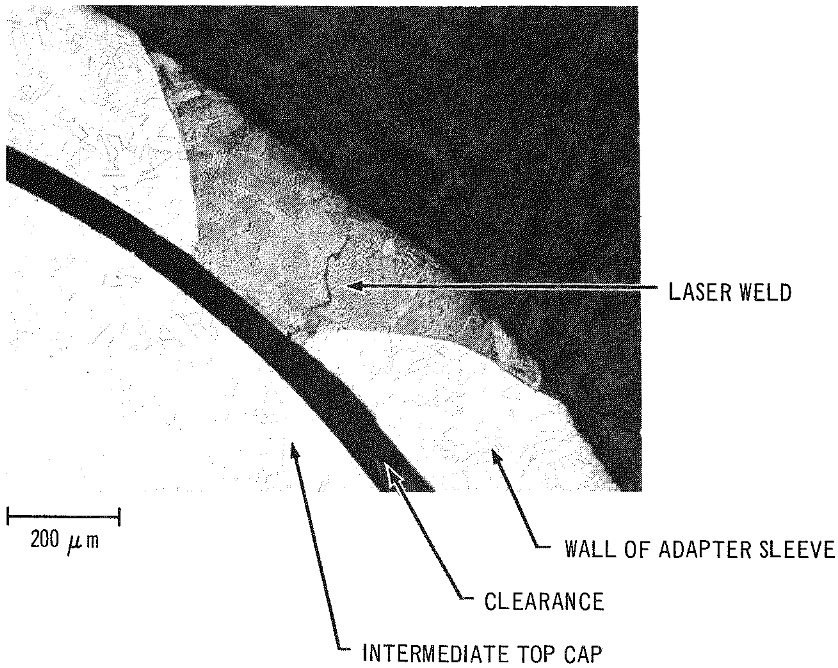


Fig. 22. Etched Transverse Cross Section through Laser Closure Weld of Xenon Charging Hole (Crack revealed)

Figure 23 shows a transverse cross section through the laser closure weld after both the laser and the TIG welds had been made. The structure is as-cast weld structure typical of the austenitic stainless steel.

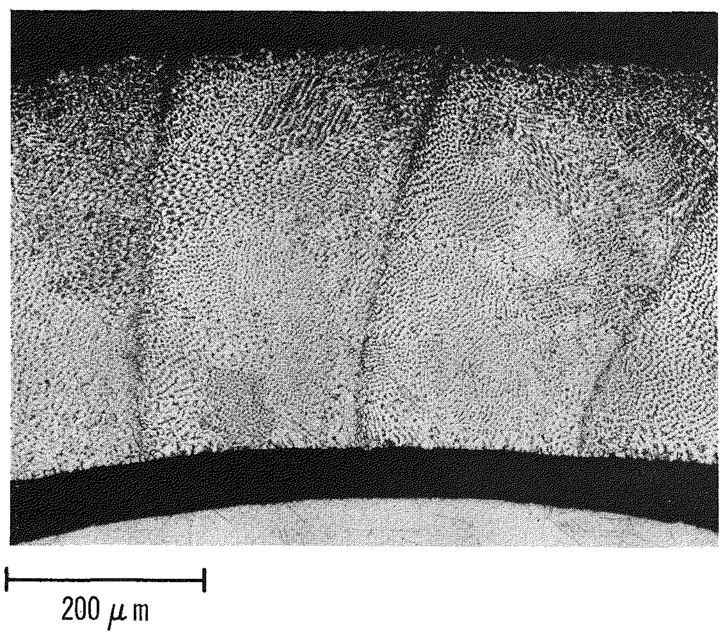


Fig. 23. Transverse Cross Section of Site of Laser Closure Weld after TIG Fusion Overlay

C. Assembling of Complete Experimental Vehicle

Experiment XX08 was assembled in the INSAT assembling area of Building 310 at ANL-East. The area consists of an assembly room 95 ft (29 m) long by 18 ft (5.5 m) wide by one story high and an adjacent room 44 ft (13.4 m) long by 18 ft (5.5 m) wide by 50 ft (15.2 m) high in which bulkhead brazing operations were performed. Special procedures were followed in the assembly area to maintain administrative control of the fuel elements and cleanliness of assembly in the area.

Upon completion of the assembling, XX08 was installed in the special INSAT shipping container and loaded onto a transport trailer for shipment to ANL-West. The activities in the various phases of the XX08 assembling are summarized below. For general descriptions of previous assembled subassemblies, see Refs. 1-3.

1. Subassembly and Internals

The first phase of assembling included installing the various internals in the subassembly (shown in Fig. 2) and assembling the components of the subassembly (e.g., the element support grid, the upper adapter, and the handling fitting). The flow diffuser, the upper flowmeter, the transition piece (a stainless-steel structure serving as a spacer between the two flowmeters), and the lower flowmeter were laid out in their respective positions. An inner hexagonal tube was installed over the flowmeters and the transition piece. This tube is about 20 in. (508 mm) long and fits snugly over the flow diffuser, flowmeters, and transition piece and, in turn, fits snugly inside the outer hexagonal tube of the subassembly. The top of the inner hexagonal tube was used as a gauge to correctly position the flowmeters and diffuser with respect to the fuel-element support grid. The flowmeter leads were inserted into the conduit tubes in grid positions 1 and 2 (see Fig. 10). The components inside the inner hexagonal tube were arc-welded together while the following precautions were observed: (1) To prevent demagnetization of the flowmeter magnets by welding currents, the welding cables were kept from the vicinity of the flowmeters; (2) the entire assembly was electrically insulated; and (3) the welder ground was connected so that the welding current did not flow through the flowmeters.

The lower adapter was lined up with the inner hexagonal tube, and when the tube was fully seated, these parts were arc-welded together, using the welding precautions discussed above.

A loading plan was prepared for placing the individual fuel elements on the T-bars of the element support grid. Each fuel element was identified by a number stamped on the fuel-element tip. Table III lists the serial numbers for all XX08 fuel elements and shows their corresponding position in the subassembly. The table also gives the serial numbers for the instruments.

The outer hexagonal tube of the subassembly was installed over the instrument leads, the fuel-element bundle, and the inner-hexagonal-tube preassembly until it engaged the lower adapter. This tube, made of Type 304 stainless steel, is 61.625 in. (1.565 m) long and has a nominal inside flat-to-flat dimension of 1.827 in. (46.41 mm) and a wall thickness of 0.040 in. (1.02 mm). It forms the outer boundary of the XX08 subassembly. After verification that the outer hexagonal tube and the lower adapter were properly aligned and that the tube was fully seated on the lower adapter, the two components were welded together.

TABLE III. Loading Positions and Serial Nos. for Fuel Elements and Instruments in XX08

Position No.[a]	Element Serial No.	Instrument Serial No.	Position No.[a]	Element Serial No.	Instrument Serial No.
1	FM Conduit		32	X8160	CP10
2	FM Conduit		33	X8110	
3	X8009		34	X8023	
4	X8012		35	X8036	
5	X8200	CP21, B01	36	X8028	
6	X8004		37	X8037	
7	X8013		38	X8038	
8	X8015		39	X8043	
9	X8008		40	X8162	CP33
10	X8151	CP5	41	X8163	CP16
11	X8016		42	X8034	
12	X8204	CP22, B03	43	X8044	
13	X8018		44	SPD tube	
14	X8103		45	X8045	
15	X8010		46	X8222	CP28, E01
16	X8207	CP23, B08	47	X8041	
17	X8152	CP9	48	X8123	
18	X8106		49	X8046	
19	X8022		50	X8225	CP30, A02
20	X8024		51	X8049	
21	X8153	CP15	52	X8042	
22	X8156	CP1	53	X8050	
23	X8158	CP7	54	X8051	
24	X8017		55	X8057	
25	X8027		56	X8166	CP3
26	X8030		57	X8170	CP17
27	X8021		58	X8124	
28	X8033		59	X8058	
29	X8108		60	X8053	
30	X8035		61	X8055	
31	X8221	CP27, B06			

[a] See Fig. 10 for location of position numbers and for types of instruments on elements.

The flow mixer was then positioned within the outer hexagonal tube above the fuel elements and welded in place. A previously assembled top end fixture consisting of the handling fitting, upper adapter, and a thermocouple support post containing two outlet-coolant thermocouples was installed next. Each instrument lead was threaded through the top end fixture. After the top end fixture was moved down to engage the hexagonal tube and it was verified that all components were properly aligned and seated, the components were arc-welded together.

With the attachment of the top end fixture to the hexagonal tube, the assembly of the XX08 subassembly and its internals was completed. At this time, a tensile test was conducted in which a force was applied to the subassembly while the elongation of the subassembly was measured by a dial indicator. This test was successfully concluded with the dial indicator returning to zero after removal of tensile force, thereby indicating no permanent deformation.

2. Extension Tube

The second phase in final assembling involved the extension tube. In preparation for this phase, each sheathed instrument lead protruding from the subassembly was cleaned and threaded through a slide piece and through the bulkhead already welded to the long oval tube. Four control thermocouples (two on each side) were temporarily spot-welded to the bulkhead for temperature control during the subsequent brazing operation. The slide piece, containing the sodium-outlet-flow holes, was securely positioned on the subassembly upper adapter and properly oriented with the bulkhead, and then welded to the bulkhead. For the welding operation, argon was purged through the sodium-outlet-flow holes.

A subassembly holding device was then inserted inside the oval tube. At its lower end, this holding device is similar to the gripper shown in Fig. 3. The device helped support the subassembly during assembling of the extension tube.

The instrument leads were then brazed to the bulkhead. For this operation, stainless-steel brazing sleeves, 0.25 in. (6.35 mm) long and with inner and outer diameters precisely sized for each lead, were strung over the leads and positioned just above the bulkhead. The subassembly and the bulkhead were then placed in a vacuum-atmosphere induction-brazing furnace. A predetermined quantity of braze powder was placed in each location, or "pocket," where an instrument lead passed through the bulkhead. Each sleeve was then pushed down into its "pocket" until it contacted the braze powder. A hydrogen flow rate of 4 L/min was established through the furnace, and the bulkhead temperature was raised to 1940°F (1060°C) as indicated by the temporary control thermocouples. The temperature was quickly raised to the brazing temperature of 2150°F (1177°C) and held for 1-1.5 min. The power was then turned off, and the bulkhead was allowed to cool in the flowing hydrogen. After cooling, the brazes were inspected for visual appearance. The four control thermocouples were then removed from the bulkhead. As a final check, the braze joints were helium-leak-checked.

An extension tube was then brazed to the 9-ft 10-in. (3.0-m)-long SPD containment tube. This extension tube serves as the SPD containment through the drywell and into the terminal box. After the brazing operation was completed, the joints were helium-leak-checked.

Within the drywell area, metal-sheathed flowmeter extension leads were spliced to the metal-sheathed leads coming from the flowmeters. The extension leads extended the flowmeter leads to the upper end of the extension tube, where flexible cables were attached to facilitate routing the conductors to receptacles in the terminal box. The extension leads were spliced to the flowmeter leads by TIG butt-welding the conductors and orbital-arc TIG welding a tubular splice over the metal sheaths.

Next, the drywell thermocouples, the sodium-leak detectors, and the drywell vent tube were installed. The vent tube provides a means of sampling the gas in the drywell. If, after XX08 is irradiated, fission gases are detected through the vent tube (indicating a leak in the drywell), the proper safety precautions can be taken when removing the terminal-box cover for instrument checkout or when removing XX08 from the reactor.

The three drywell thermocouples were fastened temporarily at elevations of 1, 36, and 227 in. (25.4, 914, and 5766 mm) above the bulkhead. The drywell vent tube was installed 1 in. (25.4 mm) above the bulkhead. Two sodium-leak detectors were fastened at an elevation 1/2 in. (12.7 mm) above the bulkhead, and one at an elevation of 35 in. (889 mm).

The instrument leads, tubes, and conduits were grouped on the outside of the inner oval tube and retained by drywell-annulus spacers (used to separate the oval tube from the extension tube). At the upper end of the tube, the leads, tubes, and conduits were fitted under the radiation shielding pieces (see Sec. II.B.2). The leads were strapped to the oval tube with metal-band straps over a distance of 250 in. (6.35 m) starting from about 1 ft (0.3 m) above the bulkhead. Above 250 in., the leads were not strapped, so that room was left to install flexible extension cables. The flexible cables facilitated routing the conductors to the terminal-box receptacles.

After all splicing operations were completed, additional drywell-annulus spacers and lead straps were installed. In the shielding zone, the leads were grouped and strapped to conform to the passages in the shielding sections. Hose clamps were used to temporarily hold the strips of shielding in place.

Next, the sensing ends of the three sodium-leak detectors were cut, and metal straps to secure them were welded to the oval tube. Finally, the drywell-annulus spacers were tack-welded to the oval tube.

The extension tube was then slipped over the wired oval tube, and the hose clamps holding the shielding sections were removed at the same time. The drywell annulus was argon-purged while the extension tube was welded to the bulkhead.

A seal cover was installed over the end of the oval tube, and a vacuum-test fixture was installed on the extension tube. The drywell annulus was evacuated, and a one-hour helium leak test was performed on the extension-tube-to-bulkhead weld.

An extension-tube support flange (see Fig. 3) was then temporarily installed. The subassembly holding device was removed, and the gripper assembly was inserted into the tube and coupled to the subassembly handling fitting.

The oval-tube flange and the static O-ring seal were then installed, followed by the cap seal and the sliding O-ring seal (see Fig. 3). The gripper support spring and flange were placed over the instrument extension leads and pushed down over the cap seal. The gripper support nut was screwed on. Six adjusting screws were used to compress the gripper support spring to an overall height of 2.563 ± 0.015 in. (65.10 ± 0.38 mm). A helium leak check of the gripper seals at the top of the extension tube was performed. The six adjusting screws were then wired together to complete the assembly of the extension tube.

3. Terminal Box

In the third and final phase of assembling, the XX08 terminal box was assembled onto the extension tube. The flux-monitor (SPD) tube was cut to length, curved, and inserted into its bellows and tube fittings (see Fig. 4).

The flowmeter leads, thermocouple leads, and SPD tube were passed through the opening in the bottom of the terminal box as the box was placed on the top of the extension tube. At the same time, the SPD tube was passed through its opening and the bellows-tube fittings in the top of the terminal box. The terminal-box connecting flange was then positioned in the correct orientation relative to the extension-tube support flange, and the two flanges were bolted together. The SPD tube and its bellows and fittings were secured inside the terminal box. The bellows and bellows-tube fitting connections were leak-checked.

The multipin connectors were wired and installed in the front cover of the terminal box, and the cover was attached to the box. The side covers were then attached, and a helium leak check was conducted on the assembly. The terminal box was evacuated and then filled with helium to 15 psig (103 kPa, gauge). This process was repeated twice. The SPD's were then installed in the SPD tube.

With the final assembling of the terminal box, XX08 was completed. The completed subassembly was then installed into its shipping container for shipment to the EBR-II site.

4. Instrument-lead Splices

As noted above, various splices of hard leads to flexible leads were made in the drywell section of XX08. Each instrument lead was spliced to a length of flexible extension cable that was connected to the receptacles in the terminal box. Because of the limited radial space available for these splices, they were staggered over an axial distance of about 18 in. (457 mm) in the region between the shielding and the terminal box. The techniques used in making these splices are summarized in the following paragraphs.

With a rotary stripping tool, the metal sheath and insulation were removed to expose a 0.75-in. (19-mm) length of the conductor wires. Additional insulation was then removed to a depth of 0.031-0.062 in. (0.8-1.6 mm) inside the metal sheath of the thermocouple lead (hard lead). The wires from each lead were positioned diametrally so that the small spaces between the sheath and the conductors and between the conductors were about equal. This sheath end was then sealed with a commercial sealant in accordance with the appropriate RDT Standard. The last 0.375-0.500 in. (9.5-12.7 mm) of each conducting wire was tinned with flux and 5% silver solder.

Standard Thermafit splice sleeves were trimmed at each end to obtain a specified overall length of 0.875 in. (22.2 mm). These sleeves, made of a heat-shrinkable plastic, had a small ring of solder at midlength.

The splice sleeve was then positioned over the connecting set of wires in preparation for the simultaneous heat-shrink/soldering of both splice sleeves. With a small heat gun, heat was applied to the splice sleeves to effect the heat-shrink/soldering. After cooling, the splices were visually examined for good flow of solder and proper shrinkage of the Thermafit splice sleeves. Electrical continuity of the metal sheath was provided by soldering a wire between the sheath of the hard lead and the braided shield of the flexible lead.

To protect the splices, each was encapsulated in epoxy resin. Each splice was placed in a casting mold, and the epoxy resin was injected into the mold with a hypodermic needle and syringe. The resin was then cured at about 140°F (60°C) for 2 hours.

The encapsulated splice was visually inspected for defects. The loop resistance and insulation resistance were measured and compared with previous measurements to ascertain that no degradation had occurred.

APPENDIX A

As-built Data for XX08 Elements

The nominal design parameters for the XX08 fuel elements are listed in Table I of the main text. Table A.1 presents as-built data for the elements. This table has been compiled from specific data and measurements that are documented for each individual element in the QA manufacturing and inspection reports.

TABLE A.1. As-built Data for XX08 Fuel Elements

DESCRIPTION	STANDARD LENGTH, 24 in.	EXTENDED LENGTH, 26 in.	STANDARD LENGTH, 24 in. WITH COOLANT THERMOCOUPLE	EXTENDED LENGTH, 26 in. WITH FUEL-CENTER AND COOLANT THERMOCOUPLES
SERIAL NO. (RANGE, NOT INCLUSIVE)	X8004 TO X8058	X8103 TO X8124	X8151 TO X8177	X8200 TO X8225
FUEL PIN NO. (RANGE, NOT INCLUSIVE)	647I-001 TO 647I-049	647I-068 TO 647I-078	647I-084 TO 647I-100	647I-051 TO 647I-067
QUANTITY	36	6	10	6
TOTAL FUEL LENGTH, mm (min/max)	342.8/343.5	343.3/343.5	343.1 343.4	343.2 343.5
FUEL WEIGHT, 10^{-3} kg (min/max)	51 81/52 26	52.00/52 24	51.91/52.19	51.19/51 49
CLADDING O.D., mm (min/max)	4.407/4.432			
CLADDING THICKNESS, mm (min/max)	0.292/0 317			
ELEMENT WEIGHT, 10^{-3} kg (min/max)	79.46 79.87	81.08 81 36	73.93/74.22[a]	82.19/82.57[a]
ELEMENT LENGTH, mm (min max)	604.8 605.2	655.7 656.0	647.5 651 5	715.8/719.3
FUEL-CLAD DIAMETRAL GAP, mm (min max)	0.470/0.546			
PLENUM VOLUME-COLD, cm^3 (min max)	2.32 2.47	3.01 3.15	2.33 2 47	2.44 2.64
FUEL VOLUME cm^3 (min max)	2.91 2.94	2.92 2.93	2.91 2.93	2.87 2.89
RATIO: PLENUM TO FUEL VOLUMES (min max)	0.80/0.84	1 03 1.07	0.80 0.84	0.85/0.91
SODIUM LEVEL ABOVE FUEL PIN-COLD, mm (min max)	27 9 30 5	19.6 22 1	27.9 30.5	26.7 35 6[b]
SODIUM VOLUME-COLD, cm^3 (min max)[c]	1.34/1 35	1.24 1.25	1 34 1.35	1.35/1.36
PLENUM GAS MIXTURE, % APPROXIMATE	70 Xe (TAG), 30 He, TRACE OF 85 Kr			70 Xe (TAG), 30 He
CLADDING VOLUME-EMPTY-COLD (CALC. per SPEC.), cm^3 (min max)	6.62 6 72	7.19 7 31	6.62 6.72	7.34 7.46
FUEL FABRICATION METHOD	CAST PIN FORM			CAST PIN FORM AND ELOX DRILLED HOLE FOR TC
FUEL CHEMICAL COMPOSITION, WT %	URANIUM — 94.42 FISSIUM (Mo-2 39, Ru-1 73, Rh-0.256, Pd-0.195, Zr-0.064, Nb-0 013, Si-0 0343)—4 6823 IMPURITIES (SEE ITEM 21) — REMAINDER			
IMPURITIES IN FUEL, ppm	Al 20, C-111, Cr-13, Fe-140, Ni-44			
FUEL ISOTOPIC COMPOSITION, WT %	(^{235}U) 66.78; (^{234}U + ^{236}U + ^{238}U) 33.22, (^{234}U + ^{236}U) 0.79			
FUEL THEORETICAL DENSITY, kg/m^3	17.6×10^3			
FUEL SMEARED DENSITY, % OF THEORETICAL	75.11			
CLADDING MATERIAL AND CONDITION	316 STAINLESS STEEL, BRIGHT ANNEALED PER SPEC. E0288-0003-02-SF			
FUEL/CLAD BOND	SODIUM			
VERTICAL LOCATION OF FUEL IN CORE	BOTTOM OF FUEL AND CORE ARE IN LINE			

(a) WEIGHT EXCLUDING SPACER WIRE AND THERMOCOUPLE.
(b) SODIUM LEVEL WITH TEMPORARY FILLER PIN.
(c) BASED ON SODIUM WEIGHT.

The fuel pins used in XX08 were obtained from the same batch of cast material, and the cladding material (Type 316 stainless steel) from the same lot of tubing. The composition of the fuel is given in Table A.1.

The assembled fuel elements with fuel-centerline thermocouples were radiographed to determine both the length that each thermocouple was inserted into the fuel pin and the location of the hot junction. Table A.2 lists these data.

TABLE A.2. Location of Fuel-centerline Thermocouples in Assembled XX08 Elements

Element No.	Subassembly Grid Position No.	Length TC Inserted into Fuel Pin,[a] in.[b]	Location of Hot Junction in Fuel Pin,[a,c] in.[b]
X8200	5	0.849	0.833
X8204	12	0.867	0.851
X8207	16	0.824	0.807
X8221	31	0.839	0.818
X8222	46	0.832	0.815
X8225	50	0.830	0.808

[a]Measured from top of pin.
[b]Conversion factor: 1 in. = 25.4 mm.
[c]A range of 0.788 to 0.912 in. was specified in assembly drawing.

APPENDIX B

Calibration Report for Permanent-magnet Sodium Flowmeters for EBR-II Instrumented Subassembly XX08

1. Results of Calibration

This appendix gives the calibration results for the permanent-magnet sodium flowmeters for use in instrumented assembly XX08 of EBR-II. The flowmeters will be mounted in tandem with the signal lead of the lower one passing through the flow channel of the upper. The lower flowmeter, AI-002 was manufactured by Atomics International to ANL P.O. 664936 and its attached specifications. The upper flowmeter, ANL-011, was originally fabricated by ANL and then rebuilt for XX08 to include an extra set of electrodes, a four-conductor cable, and shorter overall length.

The flowmeters were calibrated simultaneously in the Sodium Flowmeter Calibration System in Building 206. Calibration was done at 630, 700, and 800 ± 10°F (332, 371, and 427 ± 5.6°C) and flow rates of 10-40 gpm (0.0006-0.0025 m^3/s). At 700°F, a few low-flow runs (44-47) were made. Runs were made in both the forward and reverse flow directions.

The data for the 60 runs made are listed in Table B.1, along with the calculated flow rates. Table B.2 gives the calculated sensitivities for each run. When the sensitivities for the forward runs (F) at 700°F are plotted against flow rate, as in Fig. B.1, the data for each flowmeter comprise two sets. One set includes runs 13-34, and the other, runs 35-47. The cause of this descrepancy was judged to be a systematic error in the calibration equipment, and a study was made to determine the cause and to judge which set of data is correct. The results of the study are at the end of this appendix. The conclusion was that the flowmeters moved after run 35, allowing some sodium flow to bypass the flowmeters through the test section, and that the runs before run 36 are correct.

However, all the low-flow runs were made after run 35, and some technique is needed to establish a probable value for runs 44-47 and to extrapolate the sensitivities of the flowmeters to about 0.5 gpm (3.2×10^{-5} m^3/s).

Previous calibrations have shown that a permanent-magnet flowmeter of this design has a linear output from 10 to at least 50 gpm (0.0006 to at least 0.0032 m^3/s) and that, below 10 gpm, the sensitivity increases slightly, as shown in Fig. B.1. If the bypass flow is assumed to be a constant fraction of total flow, the ratio between the average sensitivities for the two sets of data would give a correction factor to apply to the low-flow data. Table B.3 lists the average sensitivities for the different test conditions derived from a linear regression analysis of the pertinent data of Table B.1. A point at (0, 0) was included in each analysis, because the offset had been measured to be less than 10 μV during the tests.

TABLE B.1. Calibration Data for XX08 Flowmeters

Run No.	Flow Direction[a]	Δt, s	Temp, °F[b]	Tank-expansion Correction	Flow, gal[b]	Flow Rate, gpm[b]	Signal, mV	
							AI-002	ANL-011[c]
1	R	200.8	625	1.0162	71.13	21.26	5.95	6.55-5.45
2	R	201.6	625	1.0162	71.13	21.17	5.95	6.53-5.43
3	R	201.0	630	1.0163	71.14	21.24	5.90	6.51-5.42
4	R	133.1	635	1.0165	71.16	32.08	8.95	9.75-8.05
5	R	133.3	635	1.0165	71.16	32.03	9.00	9.80-8.05
6	R	132.6	635	1.0165	71.16	32.20	9.00	9.83-8.08
7	R	402.9	630	1.0163	71.14	10.59	2.98	3.28-2.77
8	R	199.5	630	1.0163	71.14	21.40	5.98	6.58-5.48
9	R	402.5	625	1.0162	71.13	10.60	2.98	3.28-2.73
10	R	404.7	630	1.0163	71.14	10.55	2.98	3.28-2.75
11	R	196.8	700	1.0185	71.30	21.74	6.00	6.65-5.48
12	R	198.0	700	1.0185	71.30	21.60	5.97	6.57 -
13	F	200.3	700	1.0185	71.30	21.36	5.94	6.78-5.68
14	R	197.7	700	1.0185	71.30	21.64	5.97	6.57-5.48
15	R	148.3	700	1.0185	71.30	28.84	7.95	8.88-7.34
16	F	148.8	700	1.0185	71.30	28.75	7.99	9.00-7.68
17	R	147.7	700	1.0185	71.30	28.96	7.95	8.83-7.30
18	R	148.4	700	1.0185	71.30	28.83	7.99	8.78-7.24
19	R	399.9	700	1.0185	71.30	10.70	2.94	3.28-2.76
20	F	404.0	700	1.0185	71.30	10.59	2.94	3.32-2.75
21	R	400.4	700	1.0185	71.30	10.68	2.94	3.25-2.73
22	R	402.5	700	1.0185	71.30	10.63	2.94	3.30-2.72
23	F	200.0	715	1.0190	71.33	21.40	6.02	6.72-5.73
24	F	200.1	715	1.0190	71.33	21.39	6.02	6.80-5.82
25	R	199.0	715	1.0190	71.33	21.51	5.98	6.60-5.47
26	F	200.8	710	1.0188	71.32	21.31	6.00	6.92-5.81
27	F	406.0	710	1.0188	71.32	10.54	3.03	3.32-2.77
28	R	395.3	705	1.0186	71.30	10.82	3.03	3.33-2.84
29	F	397.3	705	1.0186	71.30	10.77	3.03	3.40-2.89
30	F	134.0	705	1.0186	71.30	31.93	9.05	10.26-8.70
31	R	133.9	705	1.0186	71.30	31.95	9.00	10.22-8.38
32	F	132.1	710	1.0188	71.32	32.39	9.00	10.24-8.72

TABLE B.1 (Contd.)

Run No.	Flow Direction[a]	Δt, s	Temp, °F[b]	Tank-expansion Correction	Flow, gal[b]	Flow Rate, gpm[b]	Signal, mV	
							AI-002	ANL-011[c]
33	F	37.6	710	1.0188	20.38	32.51	9.10	10.26-8.70
34	F	-	710	1.0188	71.32	-	-	-
35	F	102.6	710	1.0188	71.32	41.71	11.07	12.64-10.94
36	R	107.4	710	1.0188	71.32	39.84	11.07	12.40-10.16
37	F	105.8	710	1.0188	71.32	40.44	11.07	12.54-10.76
38	F	190.3	700	1.0185	71.30	22.48	5.98	6.80-5.80
39	R	188.8	700	1.0185	71.30	22.66	6.02	6.62-5.52
40	F	124.6	705	1.0186	71.30	34.33	9.02	10.29-8.84
41	R	126.0	705	1.0186	71.30	33.95	9.02	10.03-8.24
42	F	102.9	705	1.0186	71.30	41.58	11.05	12.64-10.86
43	R	104.2	705	1.0186	71.30	41.06	11.05	12.40-10.10
44	F	485.7	705	1.0186	71.30	8.81	2.37	2.70-2.25
45	F	487.4	705	1.0186	71.30	8.78	2.37	2.68-2.24
46	F	733.2	705	1.0186	71.30	5.83	1.58	1.79-1.49
47	F	2224.1	705	1.0186	71.30	1.92	0.525	0.60-0.497
48	F	185.3	805	1.0217	71.52	23.16	6.03	6.96-5.92
49	F	185.7	805	1.0217	71.52	23.11	6.03	6.88-5.82
50	R	186.5	805	1.0217	71.52	23.01	6.03	6.78-5.65
51	F	185.7	805	1.0217	71.52	23.11	6.05	6.90-5.87
52	F	122.6	805	1.0217	71.52	35.00	9.03	10.40-8.87
53	R	125.2	805	1.0217	71.52	34.27	9.03	10.10-8.32
54	F	102.1	805	1.0217	71.52	42.03	11.05	12.50-11.50
55	R	102.9	805	1.0217	71.52	41.70	11.05	12.30-10.80
56	F	101.9	803	1.0217	71.52	42.11	11.05	12.60-11.80
57	F	389.5	800	1.0216	71.51	11.02	3.02	3.42-2.89
58	R	387.0	795	1.0214	71.50	11.08	3.02	3.40-2.83
59	F	388.9	795	1.0214	71.50	11.03	3.02	3.44-2.88
60	F	392.1	790	1.0213	71.49	10.94	3.02	3.42-2.88

[a]F is forward, R is reverse flow direction.
[b]Conversion factors: °C = (°F - 32)/1.8; 1 gpm = 6.31×10^{-5} m^3/s; 1 gal = 3.785×10^{-3} m^3.
[c]The second signal listed for the ANL-011 flowmeter is for the extra electrodes at the outlet end of the magnet.

TABLE B.2. Sensitivity of XX08 Flowmeters

Run No.	Flow Direction[a]	Flow Rate, gpm[b]	Sensitivity, mV/gpm[b]	
			AI-002	ANL-011[c]
1	R	21.26	0.2799	0.3081-0.2563
2	R	21.17	0.2811	0.3085-0.2565
3	R	21.24	0.2778	0.3065-0.2552
4	R	32.08	0.2790	0.3039-0.2509
5	R	32.03	0.2810	0.3060-0.2513
6	R	32.20	0.2795	0.3053-0.2509
7	R	10.59	0.2814	0.3097-0.2616
8	R	21.40	0.2794	0.3075-0.2561
9	R	10.60	0.2811	0.3094-0.2575
10	R	10.55	0.2825	0.3109-0.2607
11	R	21.74	0.2760	0.3089-0.2521
12	R	21.60	0.2764	0.3042 -
13	F	21.36	0.2781	0.3174-0.2659
14	R	21.64	0.2759	0.3036-0.2532
15	R	28.84	0.2757	0.3079-0.2545
16	F	28.75	0.2779	0.3130-0.2671
17	R	28.96	0.2745	0.3049-0.2521
18	R	28.83	0.2771	0.3045-0.2511
19	R	10.70	0.2748	0.3065-0.2579
20	F	10.59	0.2776	0.3135-0.2597
21	R	10.68	0.2753	0.3043-0.2556
22	R	10.63	0.2766	0.3104-0.2559
23	F	21.40	0.2813	0.3140-0.2678
24	F	21.39	0.2814	0.3179-0.2721
25	R	21.51	0.2780	0.3068-0.2543
26	F	21.31	0.2816	0.3247-0.2726
27	F	10.54	0.2875	0.3150-0.2628
28	R	10.82	0.2800	0.3078-0.2625
29	F	10.77	0.2813	0.3157-0.2683
30	F	31.93	0.2834	0.3213-0.2725
31	R	31.95	0.2817	0.3199-0.2623
32	F	32.39	0.2779	0.3161-0.2692

TABLE B.2 (Contd.)

Run No.	Flow Direction[a]	Flow Rate, gpm[b]	Sensitivity, mV/gpm[b]	
			AI-002	ANL-011[c]
33	F	32.51	0.2799	0.3156-0.2676
34	F	-	-	-
35	F	41.71	0.2654	0.3030-0.2623
36	R	39.84	0.2779	0.3112-0.2550
37	F	40.44	0.2737	0.3101-0.2661
38	F	22.48	0.2660	0.3025-0.2580
39	R	22.66	0.2657	0.2921-0.2436
40	F	34.33	0.2627	0.2997-0.2575
41	R	33.95	0.2657	0.2954-0.2427
42	F	41.58	0.2658	0.3040-0.2612
43	R	41.06	0.2691	0.3020-0.2459
44	F	8.81	0.2690	0.3065-0.2554
45	F	8.78	0.2699	0.3052-0.2551
46	F	5.83	0.2710	0.3070-0.2556
47	F	1.92	0.2734	0.3125-0.2586
48	F	23.16	0.2604	0.3005-0.2556
49	F	23.11	0.2609	0.2977-0.2518
50	R	23.01	0.2621	0.2947-0.2455
51	F	23.11	0.2618	0.2986-0.2540
52	F	35.00	0.2580	0.2971-0.2534
53	R	34.27	0.2635	0.2947-0.2428
54	F	42.03	0.2629	0.2974-0.2736
55	R	41.70	0.2650	0.2950-0.2590
56	F	42.11	0.2624	0.2992-0.2802
57	F	11.02	0.2740	0.3103-0.2623
58	R	11.08	0.2726	0.3069-0.2554
59	F	11.03	0.2738	0.3119-0.2611
60	F	10.94	0.2761	0.3126-0.2633

[a]F is forward, R is reverse flow direction.

[b]Conversion factors: 1 gpm = 6.31×10^{-5} m^3/s; 1 mV/gpm = 15 850 mV/(m^3/s).

[c]The second signal listed for the ANL-011 flowmeter is for the extra electrodes at the outlet end of the magnet.

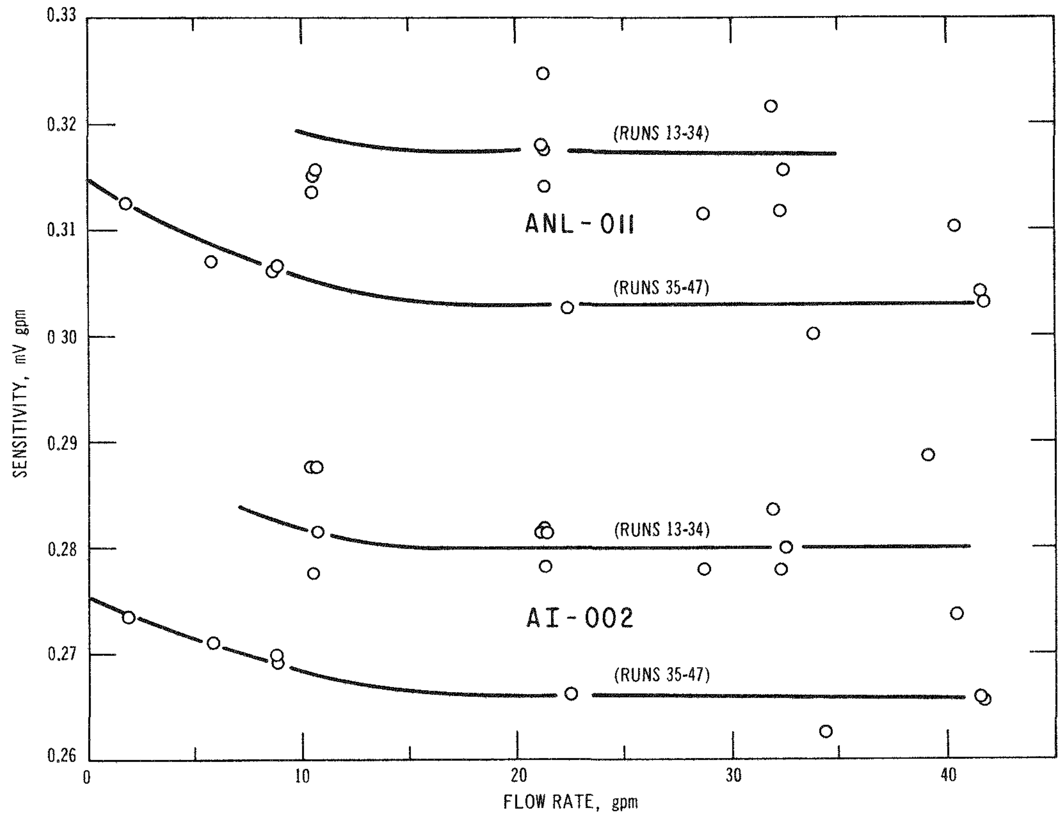


Fig. B.1. Sensitivities of XX08 Flowmeters as Function of Flow Rate: Forward-flow Runs at 700°F (371°C). Conversion factors: 1 gpm = 6.31 x 10^{-5} m^3/s; 1 mV/gpm = 15 850 mV/(m^3/s).

TABLE B.3. Results of Regression Analysis to Determine Average Flowmeter Sensitivities

Temp, °F[a]	Flow Direction	Flowmeter	Sensitivity, mV/gpm[a] Runs 1 → 34	35 → 60
630	Reverse	AI-002	0.2793	-
		ANL-011	0.3041	-
700	Forward	AI-002	0.2794	0.2677
		ANL-011	0.3175	0.3053
700	Reverse	AI-002	0.2778	0.2725
		ANL-011	0.3103	0.3056
800	Forward	AI-002	-	0.2590
		ANL-011	-	0.2954
800	Reverse	AI-002	-	0.2636
		ANL-011	-	0.2786

[a]Conversion factors: °C = (°F - 32)/1.8; 1 mV/gpm = 15 850 mV/(m^3/s).

The ratios of the equivalent sensitivities, in mV/gpm, before and after run 35 were:

700°F (371°C) Forward	AI-002:	0.2794/0.2677 =	1.044
	ANL-011:	0.3175/0.3053 =	1.040
		Average	1.042
700°F (371°C) Reverse	AI-002:	0.2778/0.2725 =	1.019
	ANL-011:	0.3103/0.3056 =	1.015
		Average	1.017

This indicates that the ratios for forward and reverse flows are different, a result that is understandable because a labyrinth can have different hydraulic resistance depending on direction of flow.

When the sensitivities for runs 35-60 are multiplied by the appropriate ratios, the results are the final calibrated sensitivities for the flow range of 10-50 gpm (0.0006-0.0032 m^3/s). (See Table B.4.) The temperature

TABLE B.4. Flowmeter Calibration Sensitivities for Flows of 10-50 gpm (63-315 x 10^{-5} m^3/s)

Temp, °F[a]	Sensitivity, mV/gpm[a]	Temp Coefficient, mV/gpm·°F[a]
	AI-002, Forward Flow	
630	-	
700	0.2794	-9.5 x 10^{-5}
800	0.2699	
	ANL-011, Forward Flow	
630	-	
700	0.3175	-9.7 x 10^{-5}
800	0.3078	
	AI-002, Reverse Flow	
630	0.2793	
700	0.2778	-6.6 x 10^{-5}
800	0.2681	
	ANL-011, Reverse Flow	
630	0.3041	
700	0.3103	-12.2 x 10^{-5}
800	0.2833	

[a]Conversion factors: °C = (°F - 32)/1.8; 1 mV/gpm = 15 850 mV/(m^3/s); 1 mV/gpm·°F = 28 530 mV/(m^3/s)·°C.

coefficients calculated directly from the 700-800°F (371-427°C) sensitivities as given in Table B.4 are somewhat higher than those from previous experience. Other flowmeter calibrations have yielded a range of temperature coefficients of 150-300 ppm/°F (270-540 ppm/°C) for the temperature range of 600-800°F (316-427°C). For a sensitivity of 0.317 mV/gpm [5024 mV/(m^3/s)] (ANL-011), this gives a range of 4.8-9.5 x 10^{-5} mV/gpm·°F [1.37-2.71 mV/(m^3/s)·°C]. A calculation of temperature coefficient based on handbook material properties yields 200 ppm/°F (360 ppm/°C). Therefore the recommended temperature coefficient for use over the entire temperature range will be lower than the test values of Table B.4. For the flow range of 10-50 gpm (0.0006-0.0032 m^3/s) and temperature range of 600-800°F (316-427°C), the recommended calibration constants are:

$$\text{AI-002:} \quad 0.2794 - \{7 \times 10^{-5} [T(°F) - 700]\} \text{ mV/gpm;}$$

$$\text{ANL-011:} \quad 0.3175 - \{7.5 \times 10^{-5} [T(°F) - 700]\} \text{ mV/gpm.}$$

The low-flow data in Fig. B.1 indicate an increased sensitivity as the flow decreases. This same performance was experienced from the flowmeters calibrated for instrumented subassembly XX07.[2] When the sensitivities of the low-flow runs 44-47 are corrected for bypass flow by multiplying by 1.042, as in Table B.5, and then plotted along with the data of the XX07 flowmeters in Fig. B.2, the similarity between the XX07 and XX08 flowmeters is observed. As an aid in extrapolating the sensitivities of the AI-002 and ANL-011 flowmeters to lower flow rates, the ratio of the sensitivities at 1 and 18 gpm (6.31 and 114 x 10^{-5} m^3/s) for the XX07 flowmeters was calculated. This ratio, which averaged 1.03, was used on the data for the AI-002 and ANL-011 flowmeters to produce the data points shown as open squares at 1 gpm (6.31 x 10^{-5} m^3/s) by which the curves were extrapolated.

TABLE B.5. Corrected Low-flow Sensitivities for Flowmeters[a]

Run No.	Flow Rate, gpm[b]	Corrected Sensitivity, mV/gpm[b] AI-002	Corrected Sensitivity, mV/gpm[b] ANL-011[c]
44	8.81	0.2803	0.3194-0.2661
45	8.78	0.2812	0.3180-0.2658
46	5.83	0.2824	0.3199-0.2663
47	1.92	0.2849	0.3256-0.2695

[a]Flow direction is forward; temperature is 705°F (347°C).
[b]Conversion factors: 1 gpm = 6.31 x 10^{-5} m^3/s; 1 mV/gpm = 15 850 mV/(m^3/s).
[c]The second signal listed for flowmeter ANL-011 is for the extra electrodes at the outlet end of the magnet.

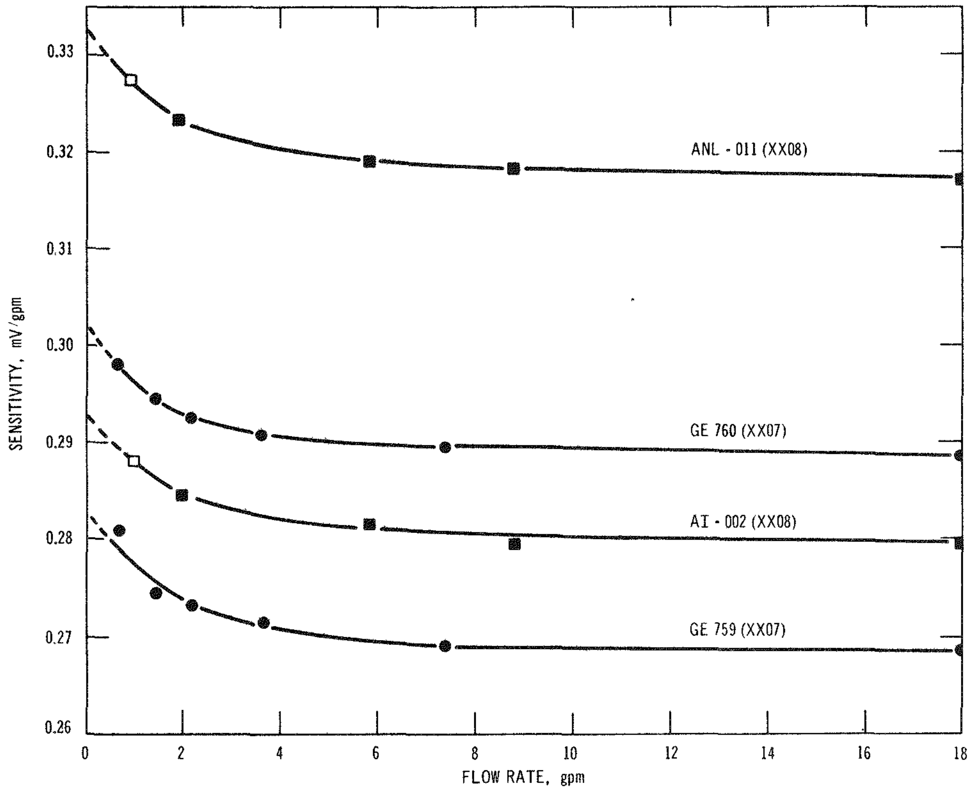


Fig. B.2. Comparison of Calibration Curves for XX08 and XX07 Flowmeters. Conversion factors: 1 gpm = 6.31 x 10^{-5} m^3/s; 1 mV/gpm = 15 850 mV/(m^3/s).

These extrapolations can be used with reasonable confidence down to 0.5 gpm (3.15 x 10^{-5} m^3/s). Below 0.5 gpm, the performance is unknown, but the same trend would be expected to continue. For example, the change from turbulent to laminar flow would theoretically yield about a 4% increase in sensitivity.

The performance of the exit electrodes of ANL-011 is plotted in Fig. B.3. The distortion of the curves, the increase in sensitivity with flow for the

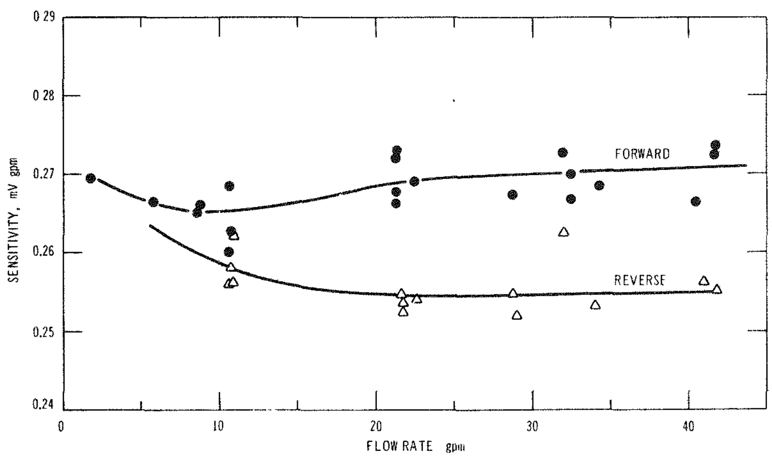


Fig. B.3. Calibration of Exit Electrodes of XX08 Flowmeter ANL-011: Temperature 700°F (371°C). Conversion factors: 1 gpm = 6.31 x 10^{-5} m^3/s; 1 mV/gpm = 15 580 mV/(m^3/s).

forward direction, and the decrease in sensitivity for reverse flow illustrate the distortion of the magnetic field caused by eddy currents in the sodium. Although intended for a test of the calibration technique of cross correlation of flow-turbulence signals, these curves may be used for flow calibration if other signals are lost.

2. Review of Error Sources in Sodium Flowmeter Calibration System of Building 206

The calibration data for the XX08 flowmeters were derived from the quantity of sodium measured by level sensors in a calibrated tank, the time from a chart drive synchronous with the power line (60 Hz), and the voltage calibration of two strip-chart recorders. Each of these data sources is examined below to determine if faulty performance could have caused the type of abnormality exhibited by the test data. This abnormality was evidenced by (a) a shift of about -4% in the calibration of both flowmeters and (b) no zero offset.

a. Possible shift in calibration of strip-chart-recorder voltage. This was ruled out, because the same shift in two separate instruments is unlikely, and calibration of the instruments before and after the abnormality showed no change.

b. Possible error in use of the millivolt calibration source. The calibration of both strip-chart recorders was periodically checked using a portable millivolt source (Technique Model 9). This possible source of error was ruled out, because the abnormality occurred in the middle of one day's runs to which a single calibration check was applied. Also, the strip-chart recorders did not indicate a shift in calibration.

c. Possible shift in time base of recorder. The chart of the recorder used as the time base was driven by a synchronous motor from the 60-Hz line. A check of the drive before and after the test did not indicate any error.

d. Possible offset in recorder calibration or a constant dc stray induced voltage. These are ruled out, because both instruments would not yield the same shift. A plot of mV output versus gpm indicates no offset.

e. Possible level-sensor shift. This is ruled out, because there was no mechanical disturbance to the tank when the abnormality occurred, a simultaneous shift of two level sensors by the same proportion is unlikely, and comparison of the end levels with an intermediate level showed no change before and after the event.

f. Possible sodium flow bypassing the flowmeters. The flowmeters were mounted in tandem in a hexagonal sleeve that constrained the sodium flow of the first to pass through the second. However, faulty assembly of the sleeve into the test section could have resulted in a marginal seal at the inlet end. Then the first test at high flow [run 35 at 41 gpm (0.0026 m^3/s)] and consequent high sodium pressure could have forced the sealing faces apart and allowed some sodium to bypass the flowmeters. This flow would be an approximate constant fraction of the main flow, resulting in an apparent percentage reduction in the millivolt output of the flowmeters.

Thus the fact that bypass flow could result in the observed data and that no other reasonable error could have resulted in the data leads to the conclusion that the probable cause of the observed abnormality is faulty assembly of the test section allowing bypass flow after the first high-velocity test.

APPENDIX C

Description of Water-flow-test Loop Procedures

1. Description of Loop

The EBR-II water-flow-test loop is constructed of Type 304 stainless steel, and operates at a constant pressure of 50-100 psig (345-690 kPa, gauge) and within a temperature range of 150-170°F (66-77°C). The maximum allowable pressure is held at 160 psig (1103 kPa, gauge) by a safety-valve setting; the maximum temperature is 200°F (93°C). Operating conditions include a maximum pressure drop through the grid test section of 100 psi (690 kPa) and a maximum flow rate in excess of 200 gpm (0.0126 m^3/s).

Figure C.1 is a schematic diagram of the loop. The flow is circulated vertically upward through the test section by two pumps [each rated at 400 gpm (0.025 m^3/s)] connected in series. Loop pressure is maintained by a secondary pressurizing pump. All heat input into the loop is generated by pumping and is regulated by a heat exchanger. The loop is charged with high-purity water.

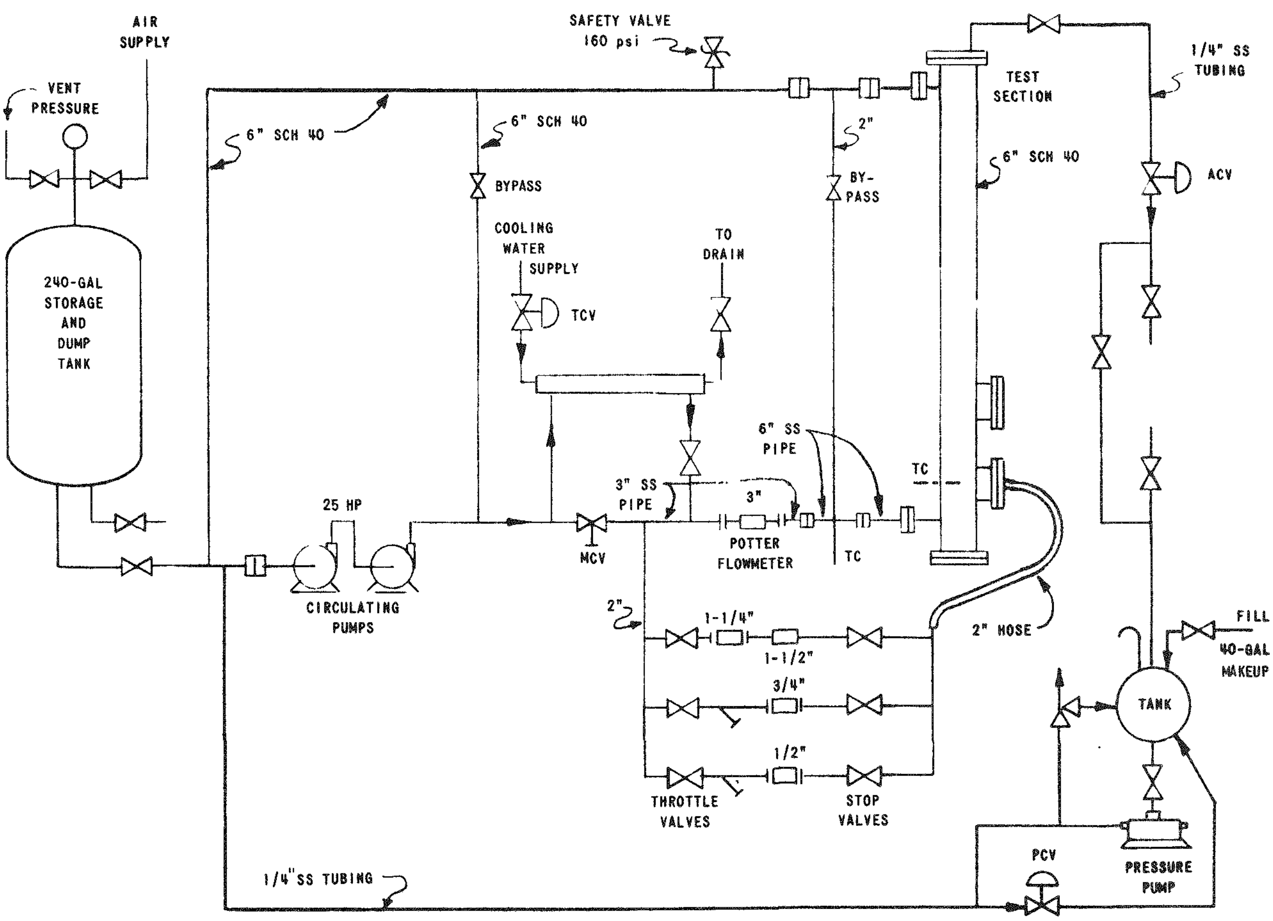


Fig. C.1. Schematic of EBR-II Subassembly Water-flow-test Loop. Conversion Factors: 1 in. = 25.4 mm; 1 gal = 3.785 x 10^{-3} m^3; 1 psi = 6.895 kPa; 1 HP = 746 W.

The flow to the test section may be directed in either of two ways. The first path is through the 3-in. (76-mm) turbine flowmeter and the 6-in. (152-mm) line to the test section. The second path is through one of the three smaller turbine flowmeters [1.5, 0.75, or 0.5 in. (38, 19, or 13 mm)] which are mounted on their respective lines and joined to a common header that is connected by a 2-in. (51-mm) hose to the test section. To ensure that no flow is leaking into the test section during a test using one of the three smaller turbine flowmeters, a blockage plate is installed between the 6-in. stainless steel pipe and the 6-in. stainless steel test section. When the 3-in.-flowmeter path is used, the flange connected to the smaller turbine flowmeters is replaced with a blank flange. When one of the three smaller flowmeters is used, a throttle valve and a stop valve are used to isolate the other two.

For the XX08 flow tests, a recently calibrated 1.25-in. (32-mm) Barton turbine flowmeter was installed in the same line as the 1.5-in. (38-mm) Brooks turbine flowmeter. All flow rates were measured during the XX08 tests with the 1.25-in. Barton turbine flowmeter.

2. Instrumentation and Control

The loop is maintained at a constant pressure by a secondary constant-displacement pump, which is fed by a makeup tank, and a pressure regulator, which controls a pressure-regulated valve. As the pressure increases, the valve remains closed. When the system pressure is achieved, the valve, receiving a signal from the pressure regulator, opens slowly to allow the excess pressure to return to the makeup tank and escape to the atmosphere.

Two thermocouples are incorporated in the loop. One sends its signal to a temperature regulator that is used to keep loop temperature constant. Part of the primary fluid is bypassed through a heat exchanger and returned to the main stream of flow before entering the test section. The cooling fluid through the heat exchanger is controlled by a temperature regulator that sends a signal to a pressure-regulated valve, limiting the amount of cooling fluid through the heat exchanger to maintain a constant temperature. The other thermocouple is in the test section, at the point of fluid entry into the subassembly being tested; the temperature is displayed on a digital temperature indicator.

The loop is continually being purged of all air. A differential-pressure cell, at the highest point in the loop, permits a small portion of the flow to return to the makeup tank, taking air with it. The amount of flow allowed to pass through the cell is controlled by two air-controlled valves operated by the cell.

Flow through the test section is measured by one of the four turbine flowmeters, all of which generate a frequency or pulse output proportional to the flow rate. The output is read out in gpm on either of the two digital readout devices. The flow rate through the test section is controlled manually by any one of the four throttle valves upstream of the test section, depending on the flow path selected.

Each individual pressure drop through the test section is measured by a differential-pressure transducer, and the electrical output from the transducer is displayed on a digital indicator.

3. Test Procedure

The following is a brief summary description of the precedure used to run the water-flow tests.

a. Perform a calibration test on the Wallace-Tiernan calibration gauge, using a dead-weight tester.

b. Perform a calibration test on the pressure transducer to be used during the water-flow test with the Wallace-Tiernan calibration gauge.

c. Assemble the XX08 water-flow-test model.

d. Install the XX08 water-flow-test model in the water-flow-looptest section. Bring the water-flow loop up to the test conditions [water temperature: 150-160°F (66-71°C); system pressure: 90-100 psig (621-690 kPa, gauge)], and record data at 11 values of steady flow.

e. Convert the water-flow-test data to the equivalent for 800°F (427°C) sodium, and determine the next flow-hole sizes (in the lower adapter) to be flow-tested.

f. When the final flow-hole sizes have been determined, run one additional water flow test to determine reproducibility.

4. Instrument Calibration

The 1.25-in. (32-mm) Barton turbine flowmeter was calibrated at the factory. According to the manufacturer, the maximum deviation was 0.17% of the indicated flow.

A Statham 100-psi (690-kPa) differential-pressure transducer was used to measure the overall pressure drop. The transducer was calibrated with a Wallace-Tiernan calibration gauge before the tests. Before the transducer calibration, the Wallace-Tiernan gauge had been calibrated with a dead-weight tester. The weights used with that tester were compared with weights traceable to the National Bureau of Standards.

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