ORNL/Sub-81/35603/1

SODIUM REMOVAL PROCESS DEVELOPMENT FOR LMFBR FUEL SUBASSEMBLIES

Prepared by
Westinghouse Advanced Reactors Division

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Consolidated Fuel Reprocessing Program

SODIUM-REMOVAL PROCESS DEVELOPMENT FOR LMFBR FUEL SUBASSEMBLIES

ORNL/Sub--81/35603/1

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Prepared by

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Madison, Pennsylvania 15663

October 1981

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SODIUM REMOVAL PROCESS DEVELOPMENT FOR LMFBR FUEL SUBASSEMBLIES

by

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October 1981

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ABSTRACT

Two 37-pin scale models of Clinch River Breeder Reactor Plant fuel subassemblies were designed, fabricated and used at Westinghouse Advanced Reactors Division in the development and proof-testing of a rapid water-based sodium removal process for the ORNL Hot Experimental Facility, Liquid Metal Fast Breeder Reactor Fuel Reprocessing Cycle. Through a series of development tests on one of the models, including five (5) sodium wettings and three (3) high temperature sodium removal operations, optimum process parameters for a rapid water vapor-argon-water rinse process were identified and successfully proof-tested on a second model containing argon-pressurized, sodium-corroded model fuel pins simulating the gas plenum and cladding conditions expected for spent fuel pins in full scale subassemblies. Subsequent water pool storage tests and post test examinations verified that 1) almost complete removal of residual sodium from the model was possible without corrosion damage at a process temperature of 145°-155°C (293°-311°F) and a total model process time of 5-6 minutes, and 2) subsequent 6-month storage in a typical reprocessing-cycle water pool at 82°C (180°F) produced no detrimental corrosion effects nor significant microstructural changes in typical spent fuel cladding.

Based on extrapolations of model proof test data, preliminary process parameters for a water vapor-nitrogen-water rinse process were calculated and recommended for use in processing full scale fuel subassemblies in the Sodium Removal Facility of the Fuel Receiving Cell, ORNL HEF. The recommended process meets HEF conceptual equipment and operational requirements. Importantly, the process meets target processing rate requirements performing sodium removal at an extrapolated rate of about 54 minutes per full-scale fuel subassembly.

SUMMARY

A rapid, water-based sodium removal process for use on spent Liquid Metal Fast Breeder Reactor fuel subassemblies during fuel reprocessing cycles was successfully developed for ORNL by the Westinghouse Advanced Reactors Division during a process development program carried out over the period August 1979 through September 1981.

The process development program consisted of three principal work tasks; Test Model Design and Fabrication, Process Development Tests and Process Proof Test. The task activities were directed toward defining an optimum water vapor-nitrogen-water rinse process which would 1) allow remote sodium removal at a rate of 30-90 minutes per subassembly on spent fuel generating up to 15 kW decay heat, 2) maintain fuel pin integrity through 300°F (149°C) sodium removal and subsequent 6-month, 180°F (82°C) water pool storage, and 3) be compatible with contingent remote facilities of the ORNL Fuel Receiving Cell, Hot Experimental Facility.

Process development was accomplished by performance of argon-water vapor-water rinse development and proof tests on a sodium-wetted 37-pin Clinch River Breeder Reactor scale model fuel subassembly with sodium-corroded and argon pressurized pins included in the proof test to simulate spent fuel cladding conditions. Model fuel pin integrity was verified by post sodium removal examinations and by metallographic examinations conducted following a 6-month water storage test of the proof tested model. Using appropriate heat and mass transfer similitudes, the test model (argon) process parameters were extrapolated to an equivalent water vapor-nitrogen-water rinse process for a full scale fuel subassembly.

As an end result, a preliminary process specification based on process proof test results was prepared for use in the Conceptual Sodium Removal System of the ORNL Hot Experimental Facility. The recommended process parameters and predicted performance characteristics for sodium removal on spent fuel subassemblies were as follows:

Process Temperature	300°F (149°C)
Nitrogen Flow, Total	∿175 SCFM
Water Vapor Flow, Total	∿175 SCFM
Subassembly Internal Flow/Total Flow	0.75-0.80
Water Vapor End Point	$\leq$100 ppm H_2
Estimated Vapor Process Time	34 minutes
Deionized Water Rinse Flow	23 gpm
Estimated Rinse Time	20 minutes

Performance Characteristics:

- Process and Process Controls can be conducted remotely.

- Process time within target of 30-90 minutes per subassembly.

- The process and subsequent storage in typical pool water for 6 months will produce no physical or corrosion damage in typical spent fuel cladding and welds.

Other significant findings realized from the conduct of the three principal tasks were as follows:

A. Multiple sodium wetting/draining operations on the test model at nominal temperatures of 1100°F/400°F (593°C/204°C) produced uniform wetting with surface sodium concentrations after draining of about 7 mg/cm^2. The level of wetting expected for full scale subassemblies is 5-10 mg/cm^2.

B. Model sodium removal tests at 145°-155°C (293°-311°F), argon-water vapor flows of 40-52 SCFM (50-65 v/o water vapor) and deionized water rinse flows of 3.3-4.3 gpm produced 1) no thermal transients, 2) manageable amounts of hydrogen, 3) no significant caustic corrosion effects in spent fuel cladding and 4) almost complete sodium removal from the model in a total process time period of 5-6 minutes.

INTRODUCTION

Current design concepts(1) for the Fuel Receiving Cell of the Hot Experimental Facility (HEF) at the Oak Ridge National Laboratory (ORNL) include receipt of spent LMFBR fuel and radial blanket subassemblies in sodium-cooled shipping casks, performance of sodium removal operations and water pool storage for periods up to six months prior to initiation of the fuel reprocessing cycle. Conceptually, the Sodium Removal System designed for initial use in the Fuel Receiving Cell must be able to process 0.5 metric tons of heavy metal per day by means of an inert gas-water vapor and water rinse process with an assumed 60-80 percent plant equipment availability. The sodium removal process and system, however, must also have the flexibility to permit processing of subassemblies not only from the Clinch River Breeder Reactor Plant (CRBRP) but also from the Fast Flux Test Facility (FFTF) and the Large Development Plant (LDP). On the basis of current FFTF/CRBRP/LDP driver and blanket fuel subassembly designs, a target sodium removal rate of 30 to 90 minutes per subassembly has been projected as being sufficient to meet the overall HEF plant throughput requirement. Of importance, the process and process control characteristics by which the Sodium Removal System fulfills the target rate requirement must also meet the following operational and qualification criterias:

A. Permit remote sodium removal from and cooling of 60-day-cooled spent fuel subassemblies generating up to 15KW of decay heat

B. Assure that deleterious effects relative to the spent fuel cladding do not occur during the sodium removal process nor during subsequent water storage.

The basic problem in a moist gas sodium removal operation results from the fact that the reaction of sodium with moisture generates heat, sodium hydroxide, and hydrogen gas. The hydrogen formed constitutes a minor, easily controlled flameability or explosion hazard. The aqueous sodium hydroxide solutions formed are the priniciple problem due to their corrosivity. At high concentrations and at elevated temperatures, sodium hydroxide solutions can corrode austenitic stainless steels significantly and may lead to caustic stress corrosion cracking.(2,3,4,5) The main factors controlling the corrosion are temperature, caustic concentration, surface conditions, stress and time. Stress level and, to a lesser extent, concentrations are generally inherent factors in the system; temperature and time are therefore the factors which must be limited in a successful moist gas sodium removal operation. At temperatures less than 121°C (250°F), corrosion has been shown to be no problem even for extended (of the order of days or weeks) exposure; as the temperatures rise above this value, exposure time must be progressively decreased to prevent corrosion damage. RDT 5-9T, "Sodium Removal Processes" limits the feed gas temperature to 88°C (190°F) in part to control reaction rate, and in part to satisfy the safe corrosion temperature requirement.

Previous small scale tests(2,3) at Westinghouse Advanced Reactors Division (W-ARD) had shown that both the water vapor-inert gas (WVN)(6) and the steam-inert gas (SIG)(7) processes could satisfactorily remove residual sodium from Type 316 stainless fuel cladding which had been prototypically corroded with sodium. It was also shown that these water-based removal methods resulted in cladding surfaces which could be stored for extended periods in water without corrosive failures. During these tests, no attempt was made to determine an optimal process for efficient and rapid sodium removal, however, the small scale test demonstrated that the sodium removal process could be accelerated without adverse effects on the cladding by use of water vapor-inert gas mixtures equal to or in excess of 50 volume percent water at process temperatures up to 71°C (160°F). It was concluded from these tests that moderate increases in reaction temperature with accompanying shortening of reaction time could be safety undertaken without unduly compromising the fuel pin cladding integrity.

In response to Union Carbide Corporation/Nuclear Division (UCC/ND), Request for Porposal No. 8-0191-62, Westinghouse ARD Proposal Number 21309(8) was issued and accepted to develop a water-based sodium removal process and process control technology for spent LMFBR fuel subassemblies.

The Development Program was initiated at W-ARD in August, 1979 under ORNL Subcontract Number 62X-35603C. This document represents the final report on this work.

DEVELOPMENT PROGRAM DESCRIPTION

Program Objectives

The objective of this program was to develop a water-based sodium removal process and process control technology for spent LMFBR fuel subassemblies which would meet the processing rate and storage requirments of the Fuel Receiving Cell for the LMFBR fuel reprocessing cycle. The process and control technology were to be optimized to meet the following operational and qualification criteria:

A. Permit remote sodium removal processing of spent fuel subassemblies at a rate of 30 to 90 minutes per subassembly.

B. Permit remote sodium removal at a process temperature of 300°F (149°C) from 60-day cooled spent fuel subassemblies generating up to 15KW of decay heat.

C. Demonstrate compatibility with the sodium removal and contingent facilities of the HEF.

D. Demonstrate that deleterious effects relative to the spent fuel cladding do not occur during the sodium removal process nor during subsequent water storage.

As process development on full scale irradiated subassemblies is neither economically practical nor necessary, a scale model was utilized for process development and proof testing to establish the optimum process. An important objective of the model tests was to establish and maintain proper hydrodynamic and reaction kinetics similitudes so that scale-up of the optimum process to full size subassemblies could be confidently predicted. In this respect, detailed heat transfer and sodium-water reaction analyses were performed by ARD for several different sizes of fuel subassemblies in an internally funded program. The results of these analyses provide a sound basis for the test model approach and are detailed in Appendix A of this report.

Program Work Scope

The work scope encompassed by the task activities of the development program included:

A. Model Fuel Subassembly design and fabrication incorporating features known to affect sodium retention and removal rate.

B. Sodium wetting operations on the model to achieve the desired levels of residual sodium as film, crevice and bulk sodium.

C. Development tests of water vapor/steam/water rinse processes on sodium-wetted models identifying the optimum candidate process or processes based on the target sodium removal rate and desired level of sodium decontamination.

D. Evaluation of cladding integrity following sodium removal operations in the process development phase of the program.

E. Exposure of pins to sodium environment prior to proof testing to produce cladding corrosion conditions typical of spent fuel.

F. Proof testing the optimum candidate process on a model containing the sodium-corroded pins verifying process control parameters.

G. Water pool storage test at water chemistry conditions typical for spent fuel water storage (defined by UCC/ND) following the process proof test.

H. Evaluation of cladding integrity following the water pool storage test in the proof testing phase of the program including destructive examinations.

I. Preparation of a preliminary fast sodium removal process and system specification for a full-scale fuel subassembly and presentation of the results to UCC/ND as a final report and an oral presentation.

Program Work Tasks

The Work Breakdown Structure for this program is given in Table 1. The experimental plan consisted of three major tasks and associated subtasks with elements of each task running concurrently. These elements were designed to address the following target development work activities:

A. Design and fabricate a scaled down fuel subassembly model with the following characteristics: configurational similitude to a full size fuel subassembly (wire wrap, crevices, hydrodynamic, heat and mass transfer characteristics); 37 pins; top and bottom hardware; readily disassembled for inspection; removable fuel pins; select pins pressurizable for stress adjustment.

B. Adapt an existing W-ARD facility for model sodium wetting, draining and transfer.

C. Design and fabricate a sodium removal vessel and install in an existing facility incorporating the required sophistication in process controls and instrumentation.

D. Carry out a series of model sodium wetting/removal operations with processing parameters defined by analyses as outlined in Appendix A. The model will be disassembled and examined after test to prove that no damage resulted from the process.

E. Modify an existing W-ARD sodium loop for sodium corrosion of model fuel pins and sodium corrode pins under sodium flow, temperature and temperature difference so that the pin surface condition suitably simulates that of spent fuel.

   The number of pins to be corroded in the 37 pin assembly will be established based on the sodium holdup patterns observed during the wetting operations and the symmetry of the assembly.

F. Carry out a final proof test of the optimal sodium removal operation, using a test model containing the sodium corroded pins. Subsequently, the test model will be stored in water of controlled chemistry as per previous corrosion tests(2) in the overall fuel reprocessing development program. After six months water storage, the test model will be disassembled for destructive metallographic examination. This will provide a direct comparison with similar results obtained in an ORNL irradiated cladding program conducted at W-ARD.

G. Prepare a preliminary fuel subassembly fast sodium removal process and component specification for a full scale system, and present the results to UCC/ND as a final report and an oral presentation.

TABLE 1
WORK BREAKDOWN STRUCTURE

Task	Subtask	Description
A		Fuel Subassembly Model Design and Fabrication
	A.1	Review Current Full Scale Subassembly Designs and Prepare Design of Test Models
	A.2	Procure Hardware and Fabricate Process Development and Process Proof Model Test Subassemblies
B		Sodium Removal Process Development Test
	B.1	Develop Test Plan for Process Development Test
	B.2	Preparation of Sodium Wetting and Removal Facilities
	B.3	Conduct Sodium Wetting and Sodium Removal Tests
	B.4	Select Optimal Sodium Removal Process
C		Sodium Removal Process Proof Test
	C.1	Develop Test Plan for Process Proof Test
	C.2	Prepare Interstitial Transfer Facility for Sodium Exposure of Model Fuel Pins
	C.3	Conduct Model Fuel Pin Exposure Test in Interstitial Transfer Facility
	C.4	Install Exposed Fuel Pins into Test Model Subassembly and Conduct Sodium Removal Process Proof Test
	C.5	Prepare Water Bath Storage Facility
	C.6	Conduct Water Bath Storage Tests
	C.7	Examine Model Fuel Pins and Evaluate Results
	C.8	Prepare Report and Presentation Documenting Results and Recommendations

PROGRAM RESULTS

For the purpose of report continuity, the results obtained from performance of the three major task activities shown in Table 1 are discussed in this section. Process recommendations and specifications for the Sodium Removal System are described in the CONCLUSIONS section of this report.

TEST MODEL DESIGN AND FABRICATION: (TASK A)

The purpose of Task A was to design and construct two scale test models of Clinch River Breeder Reactor Plant fuel subassemblies; one suitable for performing sodium removal process development tests and one for use in the process proof test. The process calculations are given in Appendix A for a 37-pin, wire-wrapped subassembly which was identified as the basis for the scale test model to be used. The 37-pin subassembly was selected on the basis of thermal-hydraulic similitudes with full scale subassemblies established during prior Westinghouse ARD fabrication and test experience in the Experimental Breeder Reactor No. II.

Model Design (Subtask A.1)

The design of the 37-Pin Simulated Model Fuel Subassembly is based on the Clinch River Breeder Reactor Plant 217-Pin Fuel Assembly design as detailed in Westinghouse ARD Drawing Number 766J584. A sketch depicting the test model is shown in Figure 1 and photographs of model parts in various stages of assembly are shown in Figures 2-4. In the Model, thirty seven wire-wrapped, simulated fuel pins are contained in a hexagonal-shaped duct section 1.92 inches across flats. Attached to the lower end of the duct is a sodium inlet assembly with simulated inlet sodium flow slots, rail assembly and a simulated internal orifice plate. The inlet assembly is attached to the duct by coarse-thread screws to permit model disassembly. A handling socket with simulated exit sodium flow channels is welded to the top end of the duct. A threaded hole was centered in the top surface of the handling socket to allow attachment of an eye bolt to support the model during testing. The overall length of the model was 25.3 inches. The top and bottom hardware of the model were configurationally similar to those of the full scale fuel subassembly so that the same flow patterns and typical sodium holdup upon draining would be produced in the model.

The model fuel pin cross section and material is prototypic Type 316 SS 20% cold worked. The pin outside diameter was .230 inches, with a cladding wall thickness of .015 inches. Each pin was wrapped with 0.067 inch diameter Type 316 20% cold worked wire in a spiral convolution with a 4.00 inch convolution pitch. Ceramic pellets, received from ORNL, each approximately 1.0 inch long with an outside nominal diameter of 0.2 inches were placed in each fuel pin to within 1.0 to 2.0 inches from the top to simulate fuel. The overall length of each model pin was 14 inches. Briefly, the stepwise fabrication of pins was carried out as follows:

A. Using the Miller 150 amp Gas Tungsten Arc Welding machine, and a rotating fixture, circumferential attachment welds were successfully made to join the Bottom End Cap to one end of the cladding.

B. Ceramic pellets, simulating fuel pellets, were loaded into each tube.

C. Top end caps were attached, to close the tube, using an identical process as that used for the lower end.

D. All welds were checked by Development Quality Assurance using the dye penetrant method. No indications were seen in preparing (57) fifty-seven pins.

E. The last step was the attachment of .067 inch diameter wire to the cladding tubes using a wire wrapping machine.

Model Fabrication (Subtask A.2)

The pin fabrication work was performed in the Fabrication Laboratory at Westinghouse ARD. Initially one pin was fully fabricated, including dye penetrant check of the attachment welds at each end, to enable the proposed fabrication process to be confirmed. The completed rod was demonstrated at a program meeting attended by an ORNL representative and was found to be acceptable. Work then proceeded with 37 pins, sufficient for one test assembly. A fabrication hold point was applied at this stage in order to determine that an acceptable fit-up would occur between the wrapped bundle and the hexagonal duct. No problems arose as a result of this exercise as a staisfactory fit-up was obtained. Work was then commenced on wrapping of the pins required for the second test assembly.

The rod-to-rod wall design clearance for the model was also based on the Clinch River Fuel Assembly nominal clearance of .002 inches. The calculation to determine this prototypic clearance using a non-standard size duct and non-standard wire is shown in Figure 5.

Procurement, fabrication and assembly of the test models were performed in accordance with W-ARD Work Plan Number 4174.(9) Manufacturing sketches (ARD-SK) to which the models were built are given in Appendix B of this report. A list of components showing material type used is shown in Table 2. Machined components were obtained from outside vendors. Fabrication of model fuel pins, assembly and welding operations were performed in the Fabrication Laboratory at W-ARD.

SODIUM REMOVAL PROCESS DEVELOPMENT TESTS (Task B)

The overall objectives of Task B as specified in the Engineering Test Plan(10) and Development Test Matrix(11) documents were as follows:

A. Prepare test facilities for sodium wetting and sodium removal operations on the development test and process proof test models.

B. Characterize sodium wetting of the test model.

C. Characterize and optimize gas flows internal and external to the test model.

TABLE 2
COMPONENT MATERIALS OF MODEL FUEL SUBASSEMBLY

ARD-SK No.	Component Description	Material Type	Quantities Per Assembly
ARD-SK-0482	Inlet Tube	316 SS (1-1/2" pipe Sch. 80)	
ARD-SK-0483	Plate	316 SS, to ASTM 276	1
ARD-SK-0484	Body	304 SS, to ASTM 276	1
ARD-SK-0485	Inlet Assembly	As Above	1
ARD-SK-0486	Support Bar	304 SS to ASTM 240	2
ARD-SK-0487	Locking Pin	304 SS, to ASTM 176	2
ARD-SK-0488 Item 1-4	Attachment Rail	316 SS, to ASME SFA 3.5	7
ARD-SK-0489	Bottom End Cap	316 SS to ASME 276	37
ARD-SK-0490	Top End Cap	316 SS to ASTM 276	37
ARD-SK-0491	Cladding	316 SS 20% Cold Worked to WARD E-Spec #953016	37
ARD-SK-0492	Fuel Rod Assembly	As Above	37
ARD-SK-0493	Handling Socket	304 SS to ASTM 479	1
ARD-SK-0494	Orifice Plate	304 SS to ASTM 276	1
ARD-SK-0495	Duct	304 SS Hex Tube to ASTM 240-67	1

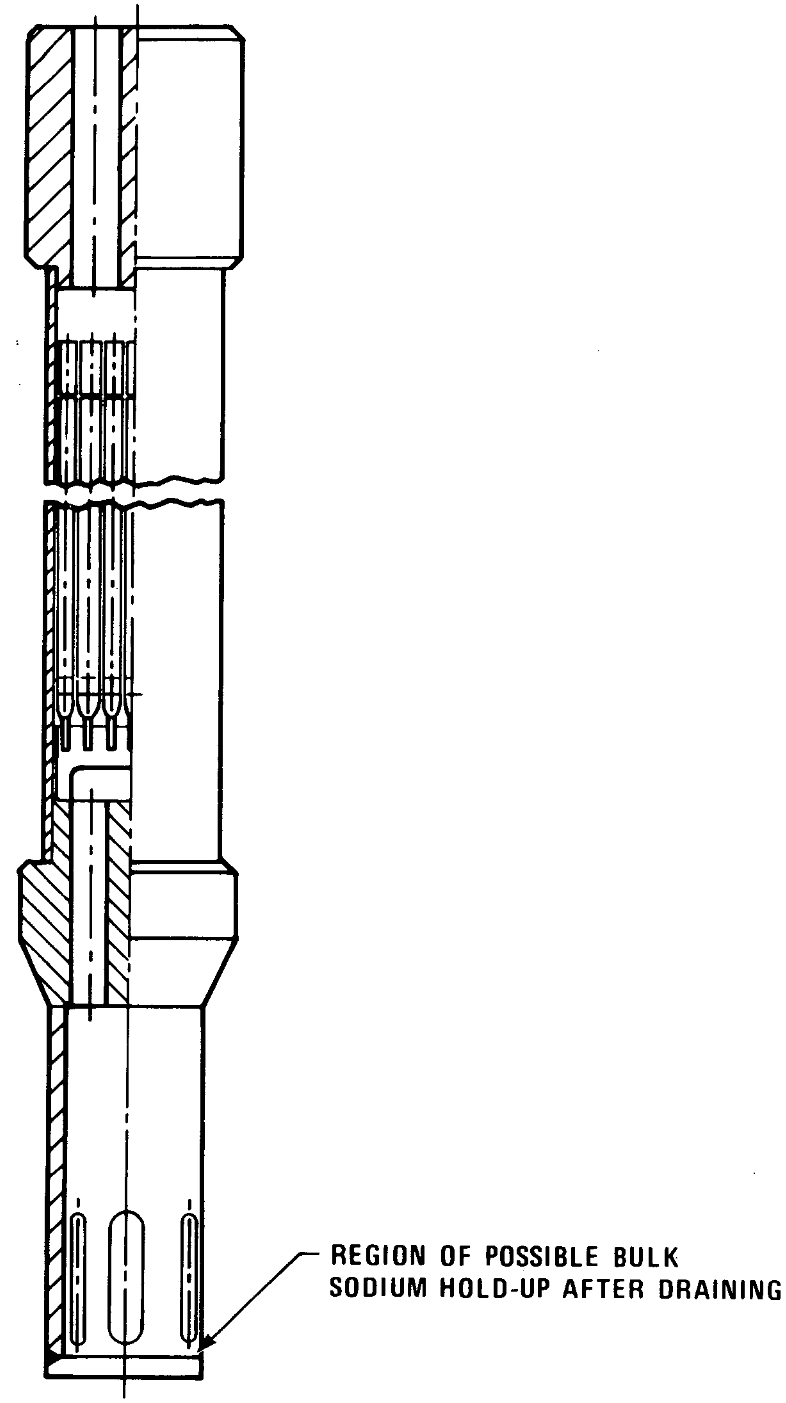


Figure 1. 37 Pin Simulated Fuel Subassembly for Sodium Removal Test

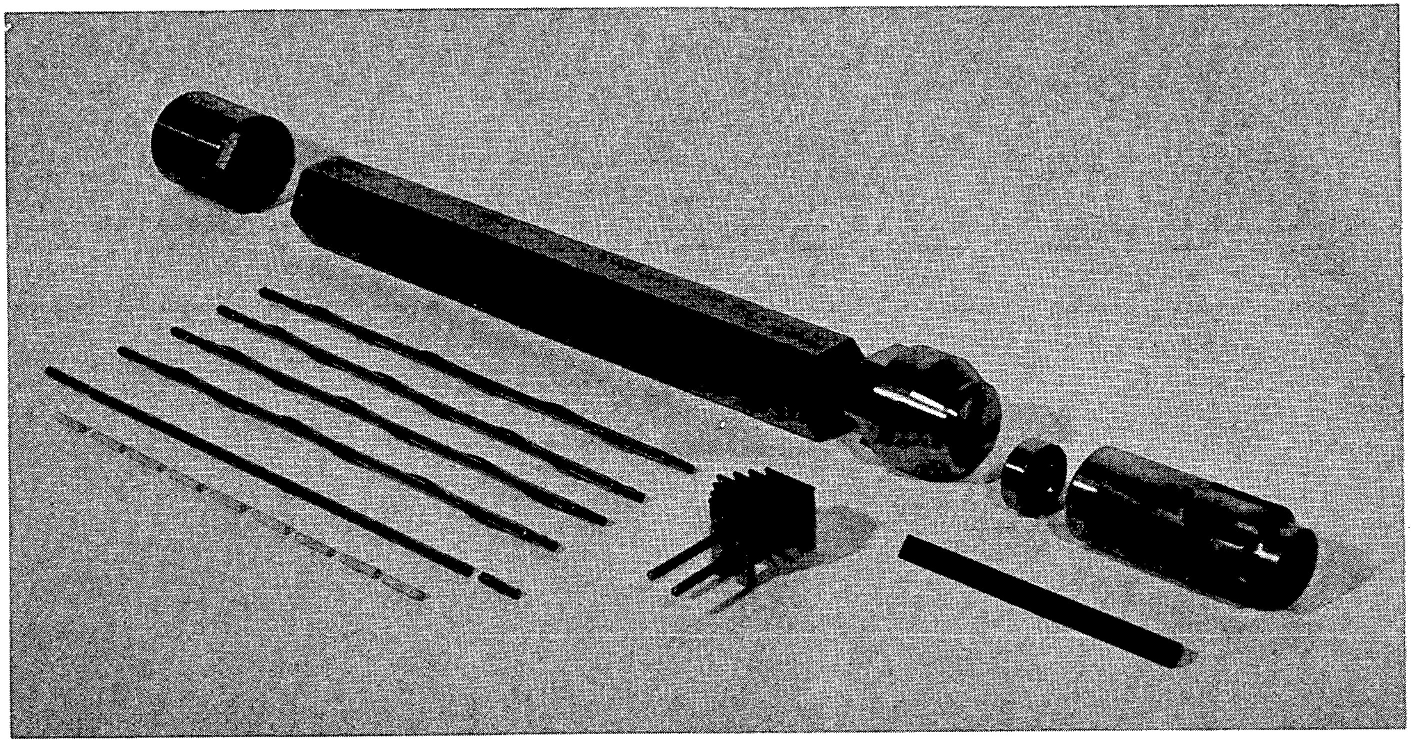


Figure 2. Components of Test Model Fuel Subassembly (MFSA)

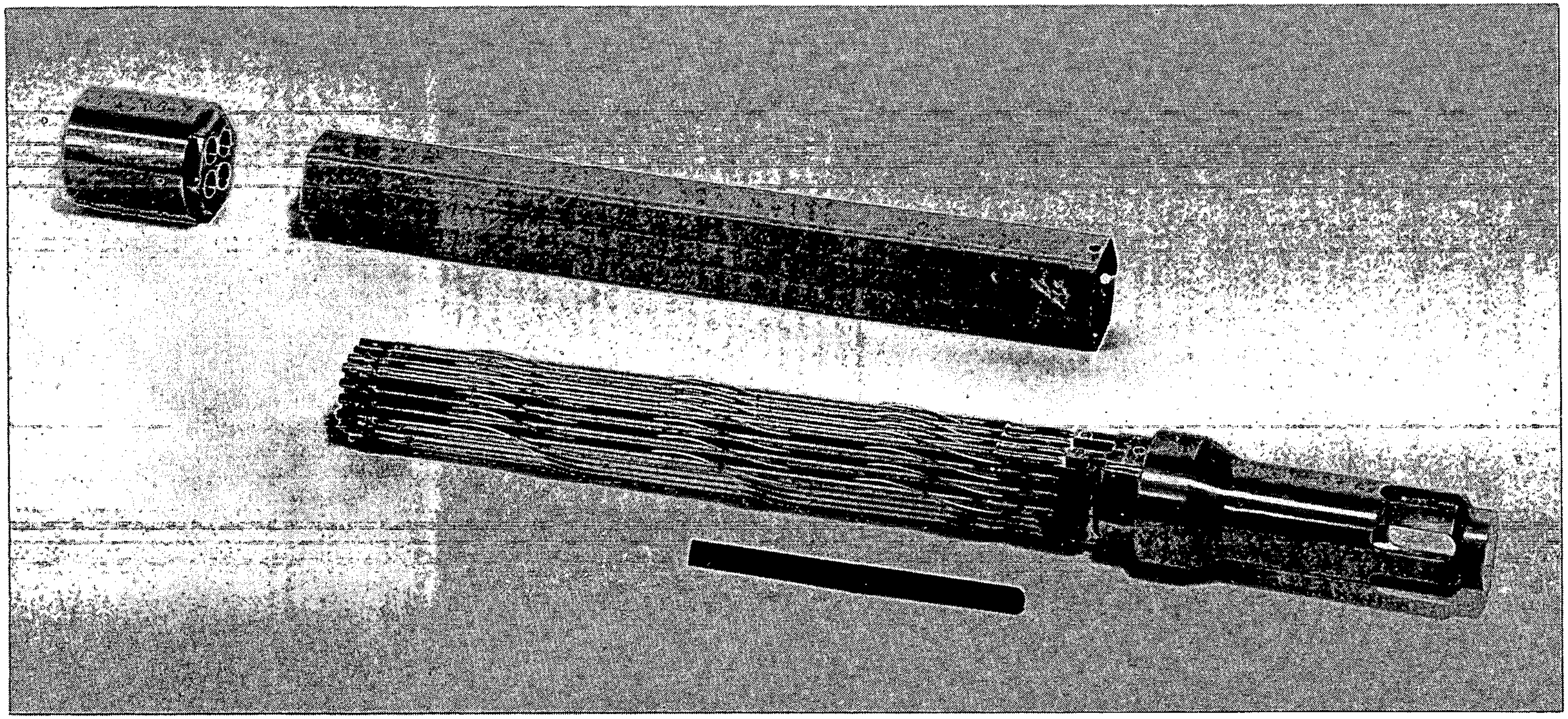


Figure 3. Pin Bundle-Inlet Nozzle Assembly, Duct and Handling Socket of MFSA

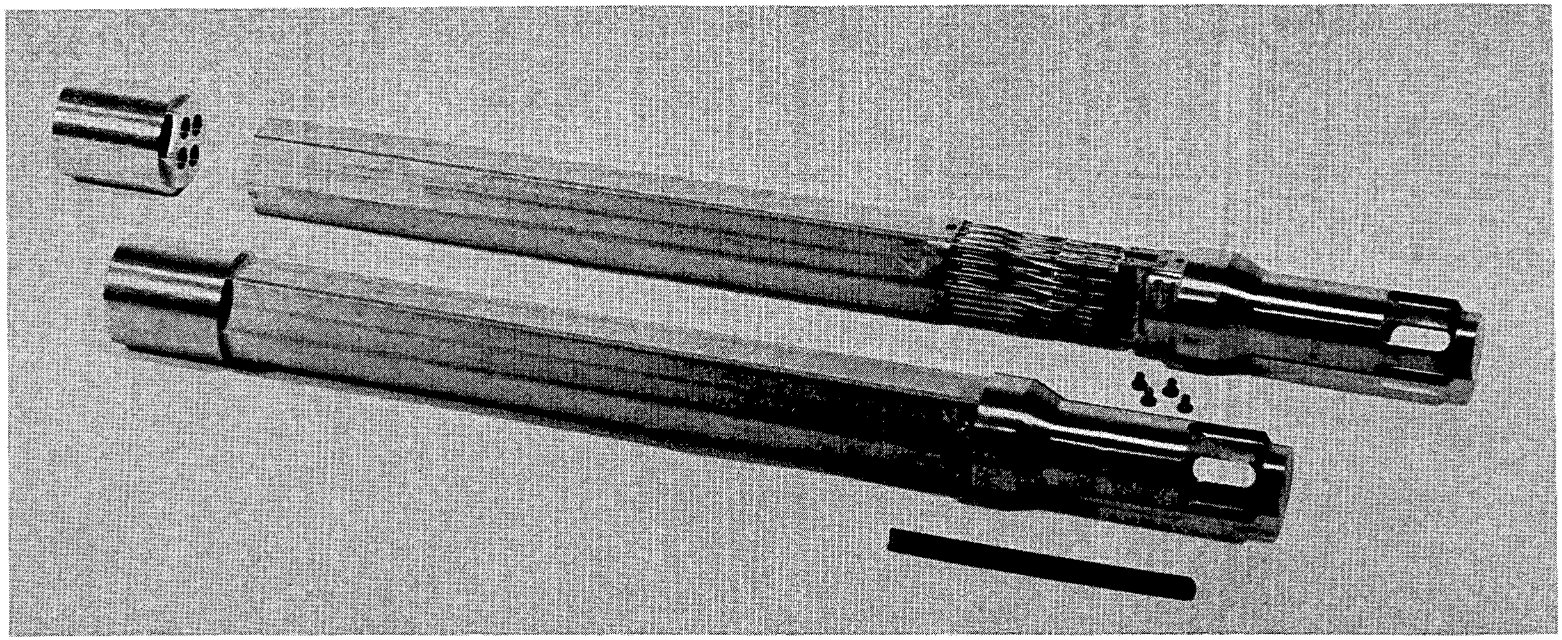
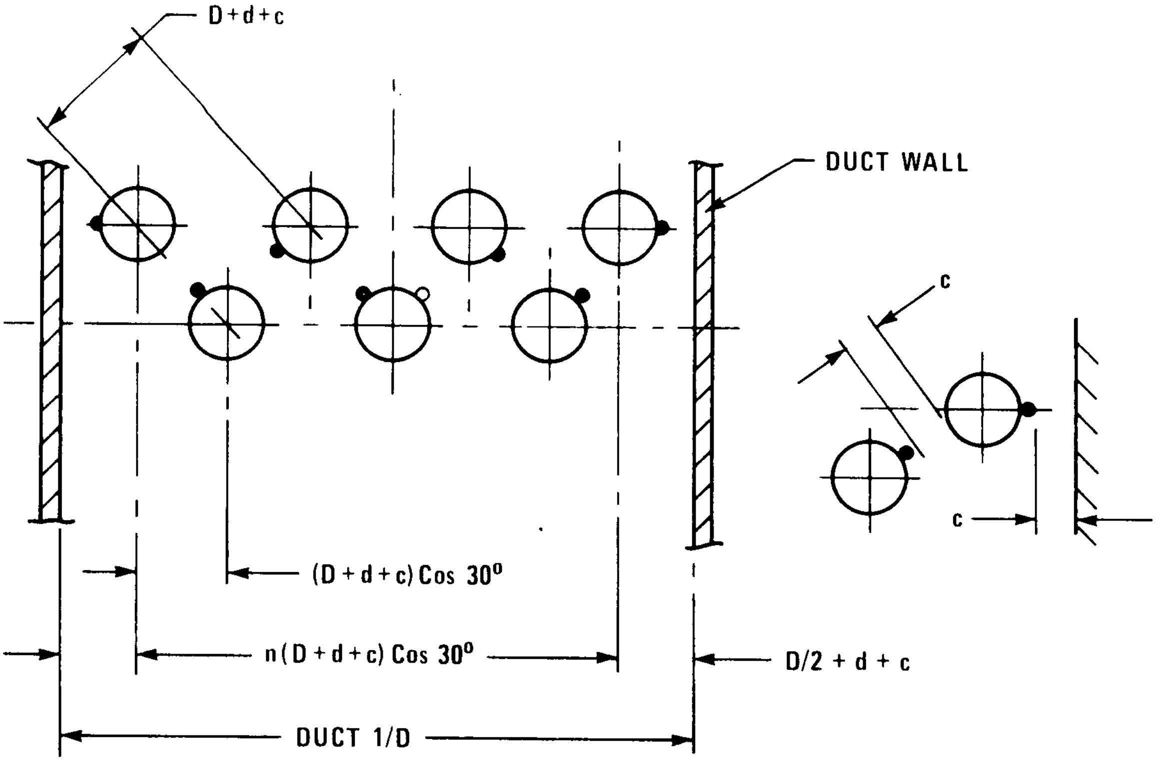


Figure 4. Assembled MFSA



DUCT 1/D = n(D + d + c) Cos 30° + 2 (D/2 + d + c)

WHERE D = ROD DIA. = .230
d = WIRE DIA. = .067
c = CLEARANCE
n = NO. OF SPACES = 6 FOR 37 PINS

$1.920 = 6(.230 + .067 + c)\ .866 + 2(.115 + .067 + c)$
$1.920 = 6(.297 + c)\ .866 + 2(.182 + c)$
$1.920 = 6(.2572 + .866c) + .364 + 2c$
$1.920 = 1.5432 + 5.196c + .364 + 2c$
$1.920 = 1.5432 - .364 = 7.196c$
$c = .0018$ CLEARANCE

Figure 5. Method of Determining Rod to Rod Clearance Across Fuel Assembly

D. Perform sodium removal process development tests at selected flow levels of argon, water vapor and water rinse sufficient to establish optimum process parameters to be used in the Process Proof Test phase of the Program (Task C).

The results from activities conducted under Task B are summarized below for each of these objectives.

Sodium Wetting Facility (Subtask B.2)

The sodium wetting and sodium removal test vessels and supporting control equipment were mounted on a common angle iron rack located in the W-ARD Sodium Removal Facility. Photographs of the facilities are shown in Figures 6-9. Schematics of the sodium wetting and sodium removal systems are depicted in Figures 10 and 11, respectively.

The sodium wetting system featured an all stainless steel vessel, dump tank and piping capable of full length immersion of the test models in static sodium under cryogenic argon. The vessel was heated by clam shell heaters and immersion thermocouples were spaced along the wetting vessel to monitor sodium temperatures during sodium fill, wetting and draining operations. Sodium filling and draining operations were performed by alternate argon pressurization of the dump tank and wetting vessel respectively with the sodium fill level monitored by a penetrating thermocouple located at the top of the wetting vessel. A 4-inch ball valve and plexiglas transfer vessel were bolted to the top flange of the wetting vessel to permit installation and removal of the models under argon.

A plexiglas transfer vessel with glove ports was fabricated for argon-inerted transfer of the sodium-wetted test model to the sodium removal vessel. A mini-beam load cell was installed on an extended plexiglas platform to permit weighing of the unwetted and wetted model while suspended in the transfer vessel. A schematic of the transfer vessel and load cell arrangement is shown in Figure 12 and depicted photographically in Figures 8 and 9.

Calibrations were completed of the load cell system shown schematically in Figure 13 for anticipated residual sodium inventories on drained models (40-50 grams). A standard lead weight was prepared duplicating the weight of the unwetted development test model plus associated hoist rod; the standard weight to be used in standardizing initial load cell recorder readings prior to weighing of sodium-wetted models. The results of load cell recorder response for known add-on weight changes are given in Figure 14 for 10 volt load cell DC power input. A bucking resistance circuit was added to the load cell output circuit to provide additional sensitivity.

Sodium Removal Facility (Subtask B.2)

The sodium removal test system shown in Figure 11 features a 3-inch stainless steel removal vessel with a lower side inlet for steam-argon and water rinse injection, a bottom drain and a top side vent discharging gas and water to the building exterior. The vessel top flange accomodates a 4-inch ball valve to which the transfer vessel can be mated and through which the sodium-wetted models were passed under argon preparatory to sodium removal operations. In the vessel, the wetted models are lowered through a top orifice plate and seated on a bottom perforated ledge which mates with the tapered outer surface of the test model inlet nozzle. The orifice plate inner diameter was machined to provide a gap with the outer surface of the handling socket of the test model; the gap size controlling flow division internal and external to the test model. Thermocouples were spaced along the surfaces of the vessel and at various locations on the inlet piping to monitor steam, argon and vessel temperatures. A single, sheathed thermocouple penetrated the wall of the removal vessel at approximately mid-length of the test model to monitor temperatures inside the removal vessel.

In the sodium removal test system, flows of cryogenic argon, dry steam and deionized rinse water to the removal vessel were valve regulated, solenoid actuated and could be pre-set to desired levels for timed delivery during the water vapor-argon and water rinse reaction steps of the process. The facility included:

A. System inlet argon flows which could be pre-set for two flow levels by a parallel solenoid operated (SV1, SV2) ball valve regulated (RV1, RV2) arrangement. Inlet argon flow was monitored by a rotameter (FAR) calibrated as a function of inlet argon pressure (P1) as depicted in Figure 15. Inlet argon flows to about 52 SCFM could be controlled and monitored.

B. An in-line 3 KW argon heater and trace heating of argon piping capable of heating and maintaining inlet argon temperatures in excess of 300°F (149°C).

C. An inlet steam flow system capable of delivering steam at two pre-set levels by means of pneumatic valve (ISV) openings controlled through two parallel solenoid-operated (SV5, SV6) argon-actuated pressure regulators (PR5, PR6). Steam flow from a 72 KW electric steam generator was monitored by a digital display turbine meter (TM) previously calibrated for 300°F steam flows as shown in Figure 16. Calibration curves for pressure regulator settings as a function of turbine meter steam flows are given in Figure 17. Maximum turbine meter limits and pneumatic steam valve openings limited system steam flows to about 26 SCFM.

D. A pump-assisted, solenoid valve controlled deionized water rinse system capable of injecting water at flows to 4.3 gpm on demand to the bottom of the removal vessel. Deionized water was supplied by a Tri-Bed ion-exchange demineralizer. Discharge rinse waters were collected in a 55-gallon stainless steel drum.

E. An electrical resistance probe mounted in the effluent line from the removal vessel to monitor sodium hydroxide concentrations in the discharge rinse waters. The probe read-out system is shown in Figure 18. Recorder millivolt out-put readings for the probe immersed in standard sodium hydroxide solutions are given in Table 3.

F. An effluent thermal conductivity hydrogen analyzer capable of continuous monitor and display of effluent argon hydrogen

TABLE 3

RECORDER OUTPUT OF EFFLUENT RESISTANCE PROBE FOR VARIOUS SODIUM HYDROXIDE SOLUTIONS

Probe[a] Environment	Recorder Reading, volts[b]
Argon	0
Deionized Water	0.01
4 ppm NaOH	0.10
40 ppm NaOH	0.19
400 ppm NaOH	0.34
4000 ppm NaOH	0.47

(a) All liquid stirred, experiments at ambient temperature, 22° ± 1°C.

(b) 1 volt scale (1 div. = 0.01 volt); probe system has R_V = 500 ohms, E = 1.5 volt DC, R_1 = 1000 ohms (R_V adjusted to give air reading shown). Cell constant of probe is 0.1 cm^{-1}.

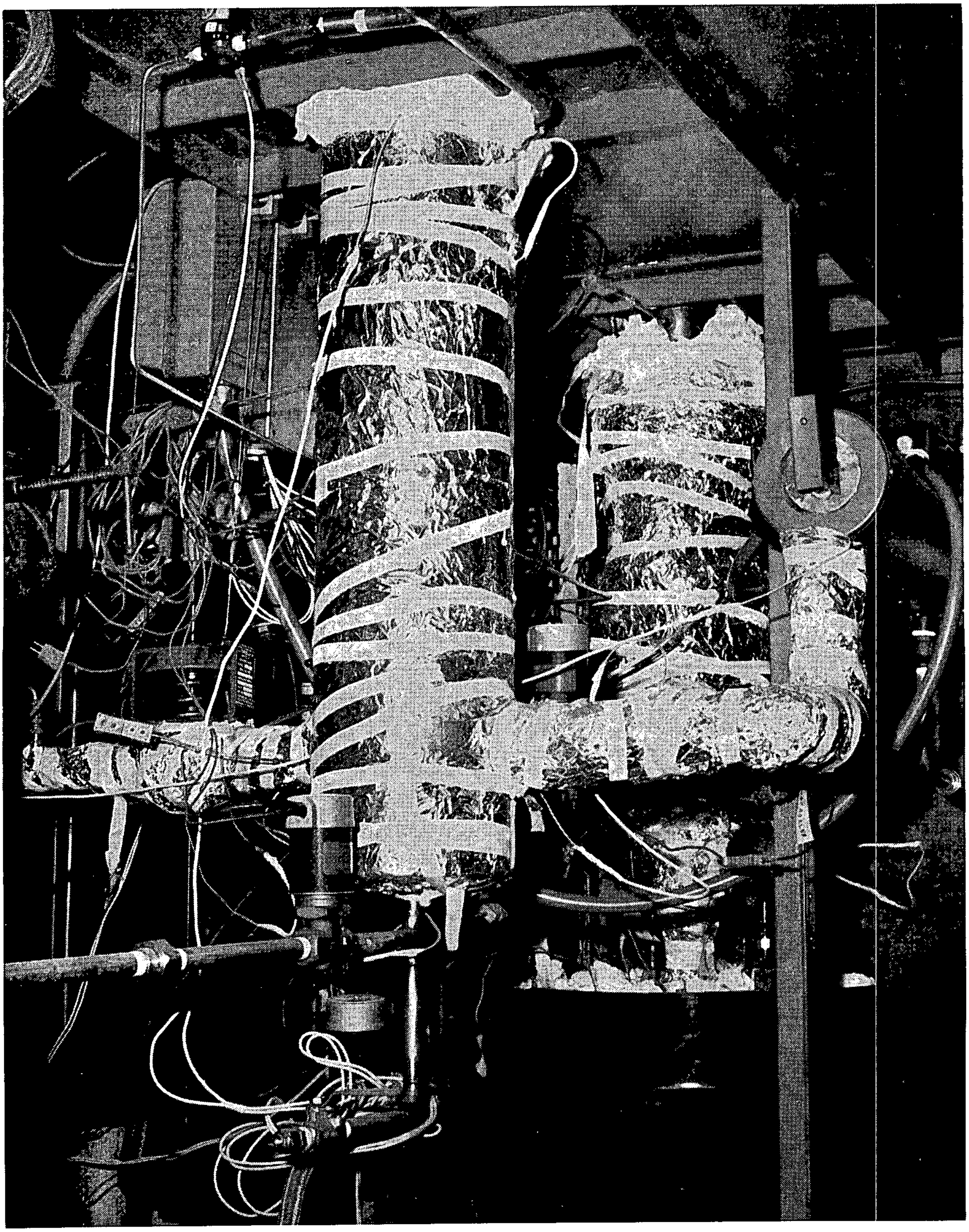


Figure 6. View of MFSA Sodium Removal (Foreground) and Sodium Wetting (Background) Systems. The Main Argon Heater is Shown on Right and the Blue Inlet Steam Valve on Left

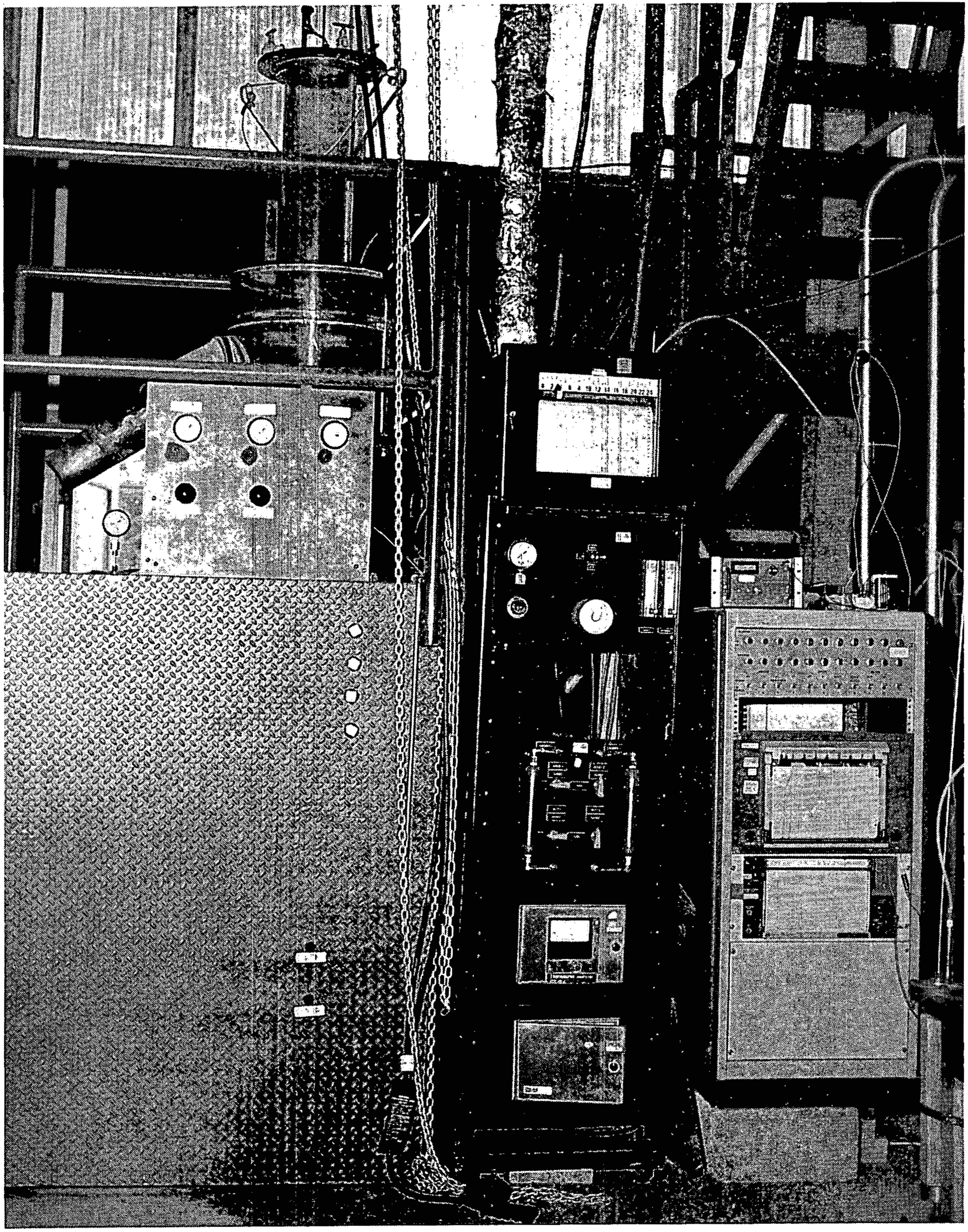


Figure 7. Control Console of MFSA Sodium Wetting and Sodium Removal System

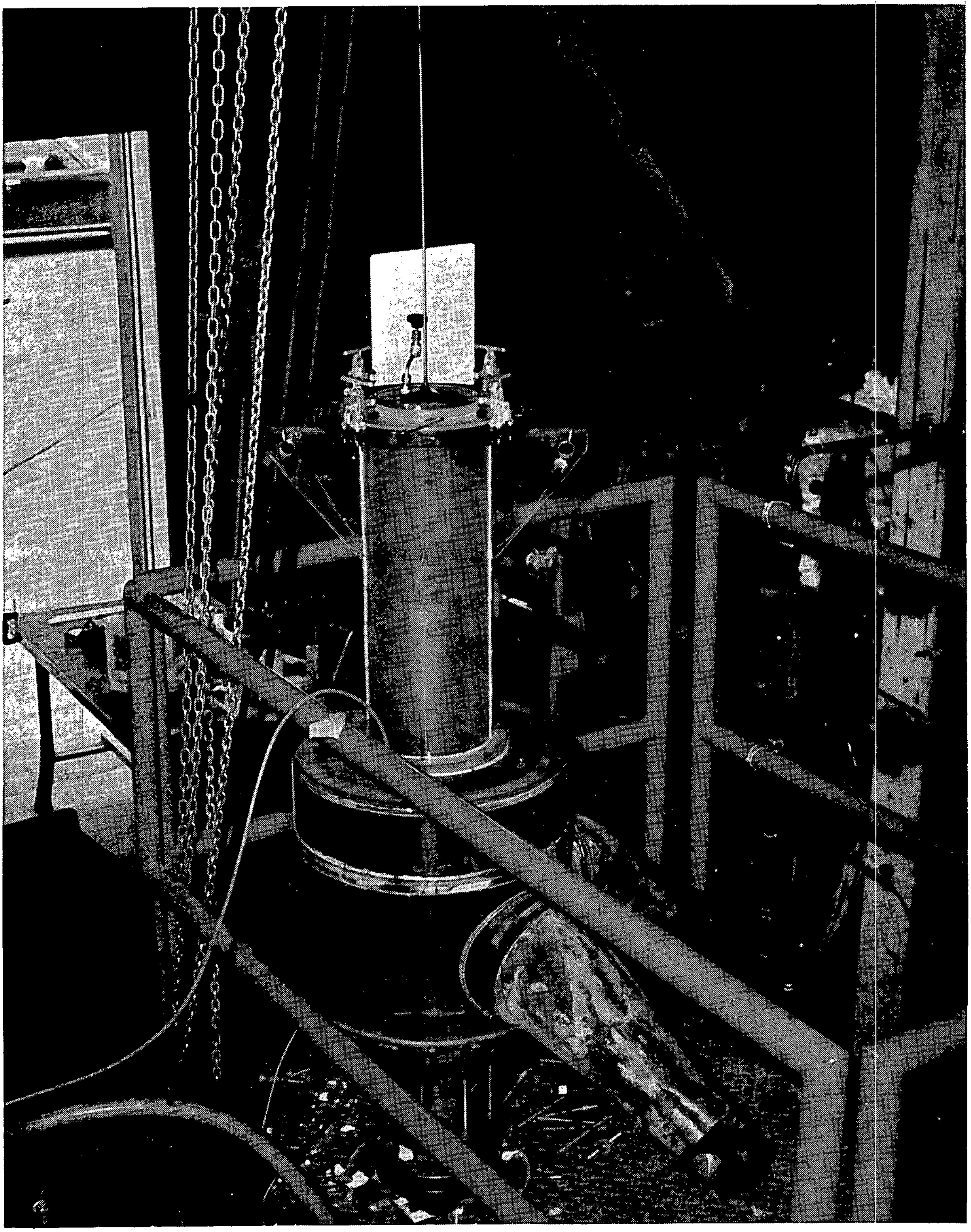


Figure 8. MFSA Transfer Vessel with Test Model Suspended in Transfer Position. Transfer Vessel is Mounted on the Top 4-Inch Ball Valve of the Sodium Wetting Vessel

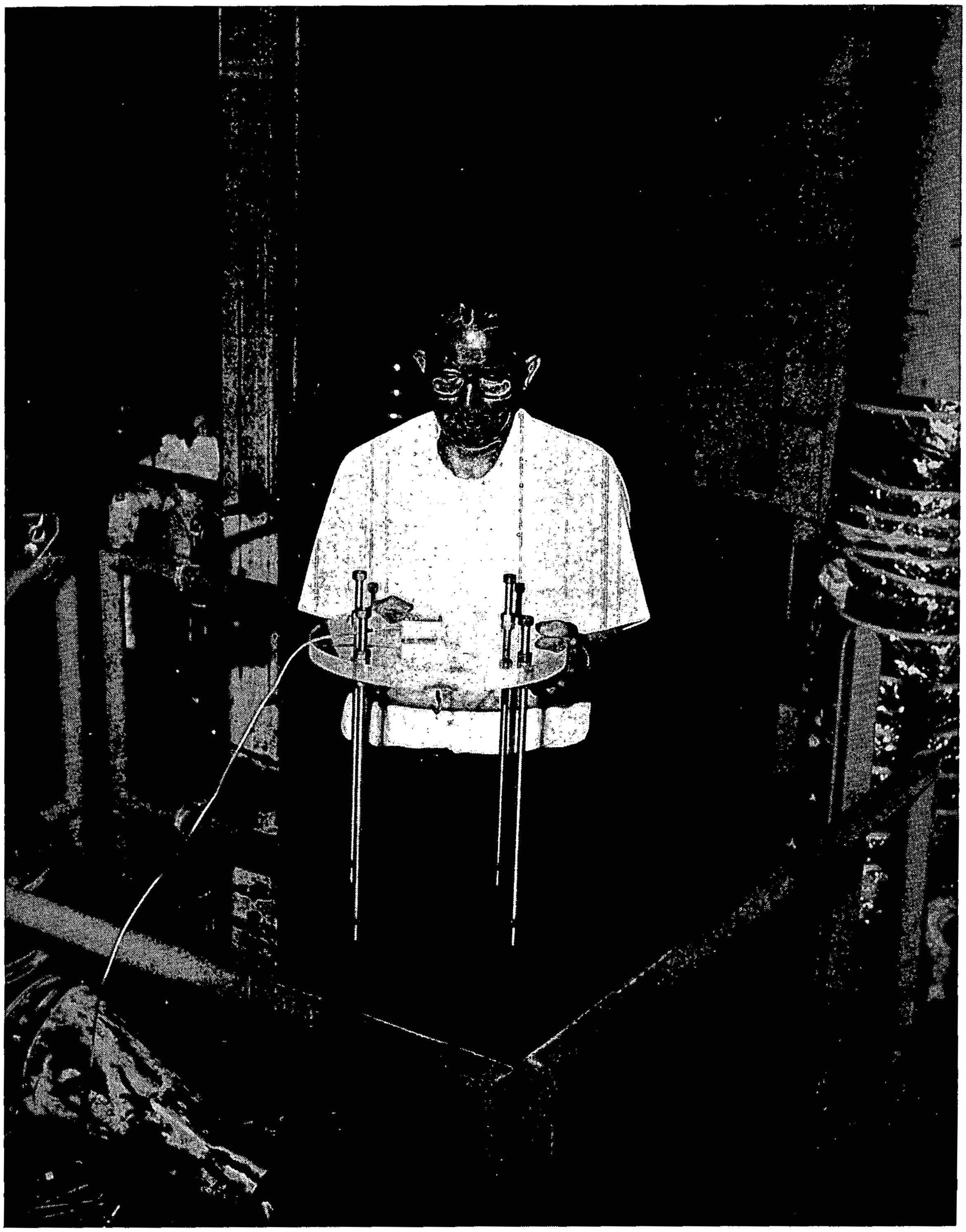


Figure 9. MFSA Load Cell and Support Plate for Weighing of Sodium-Wetted Test Models

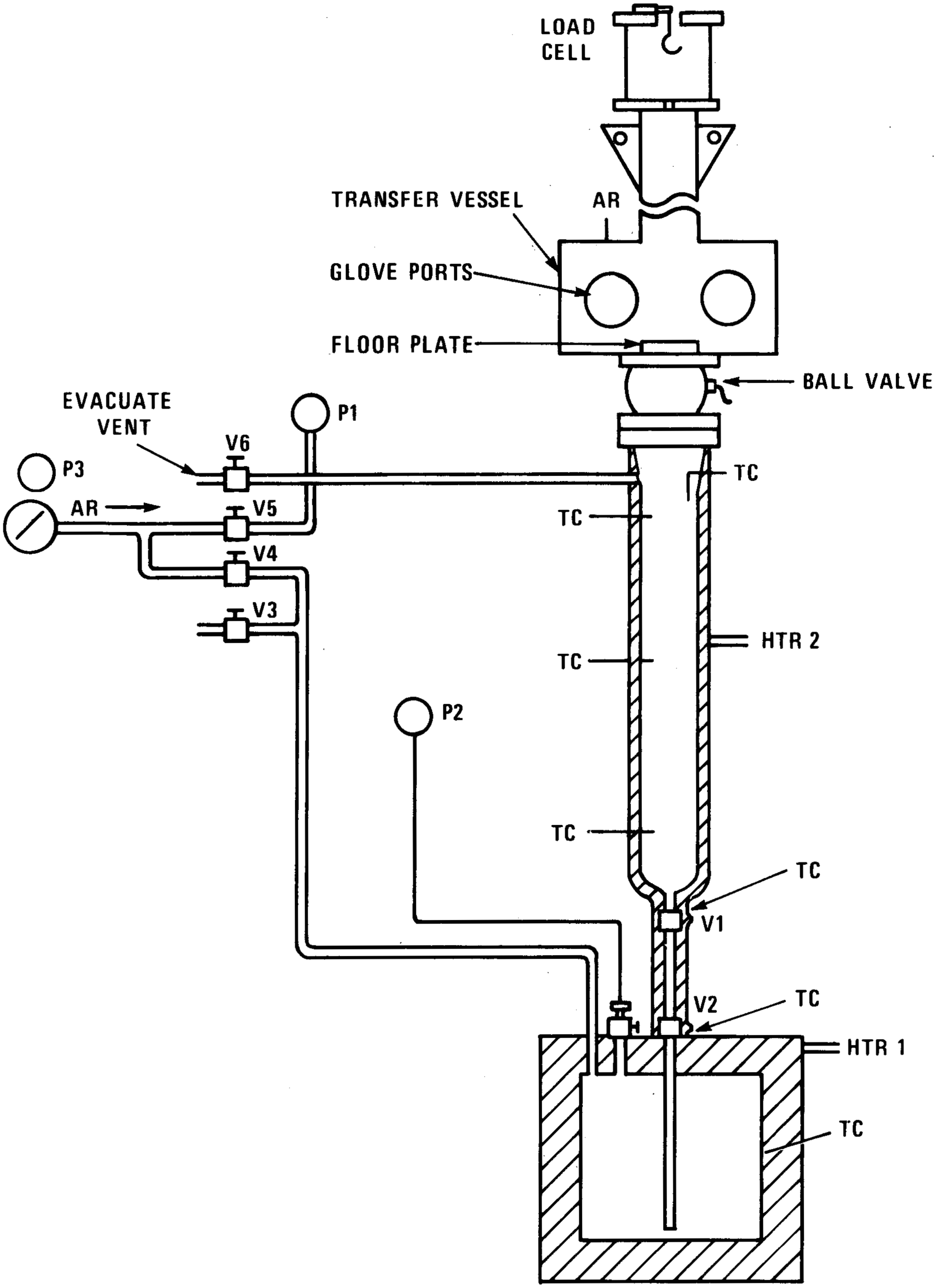


Figure 10. Schematic of Test Model Sodium Wetting System

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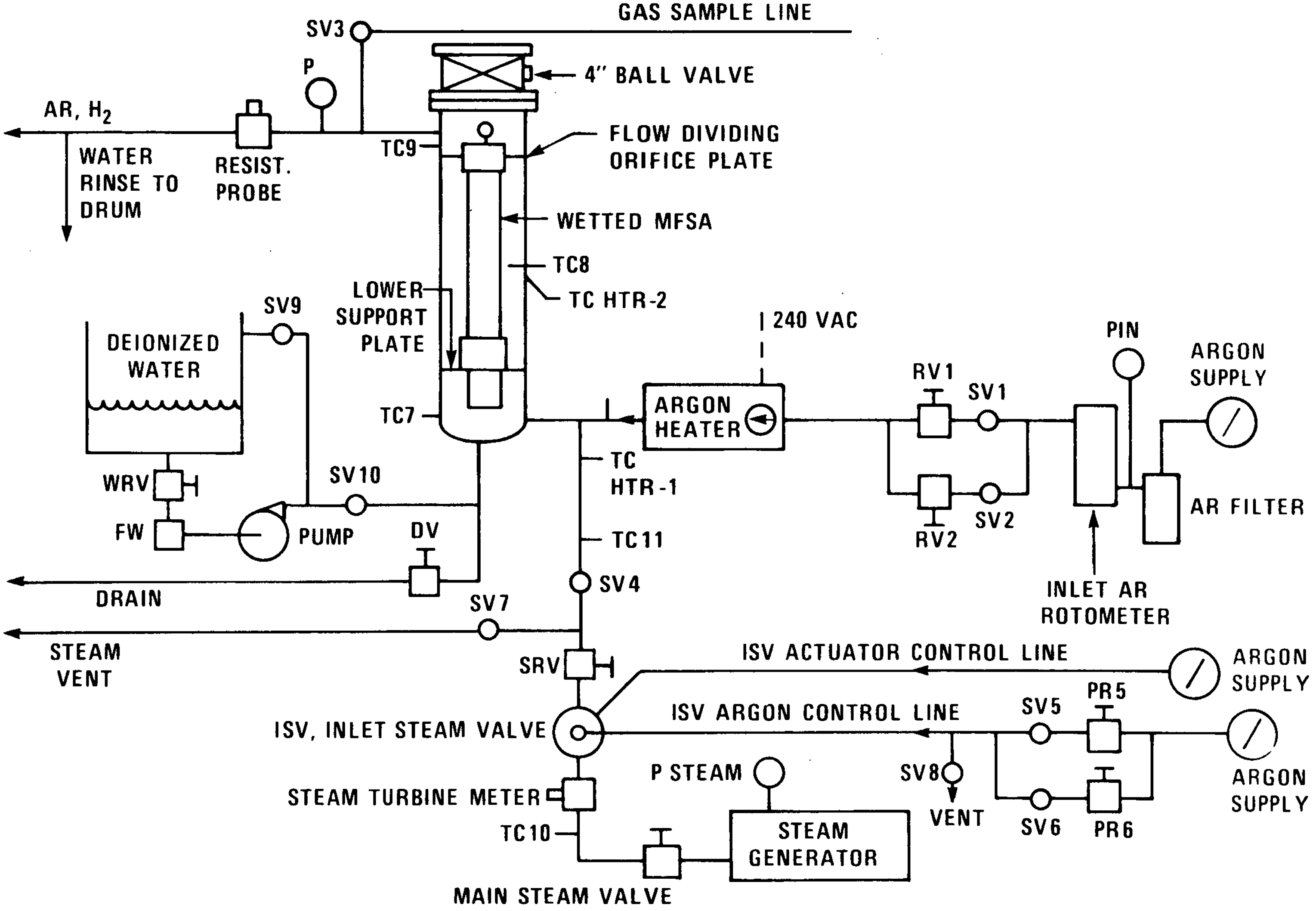

Figure 11. Schematic of Test Model Sodium Removal System

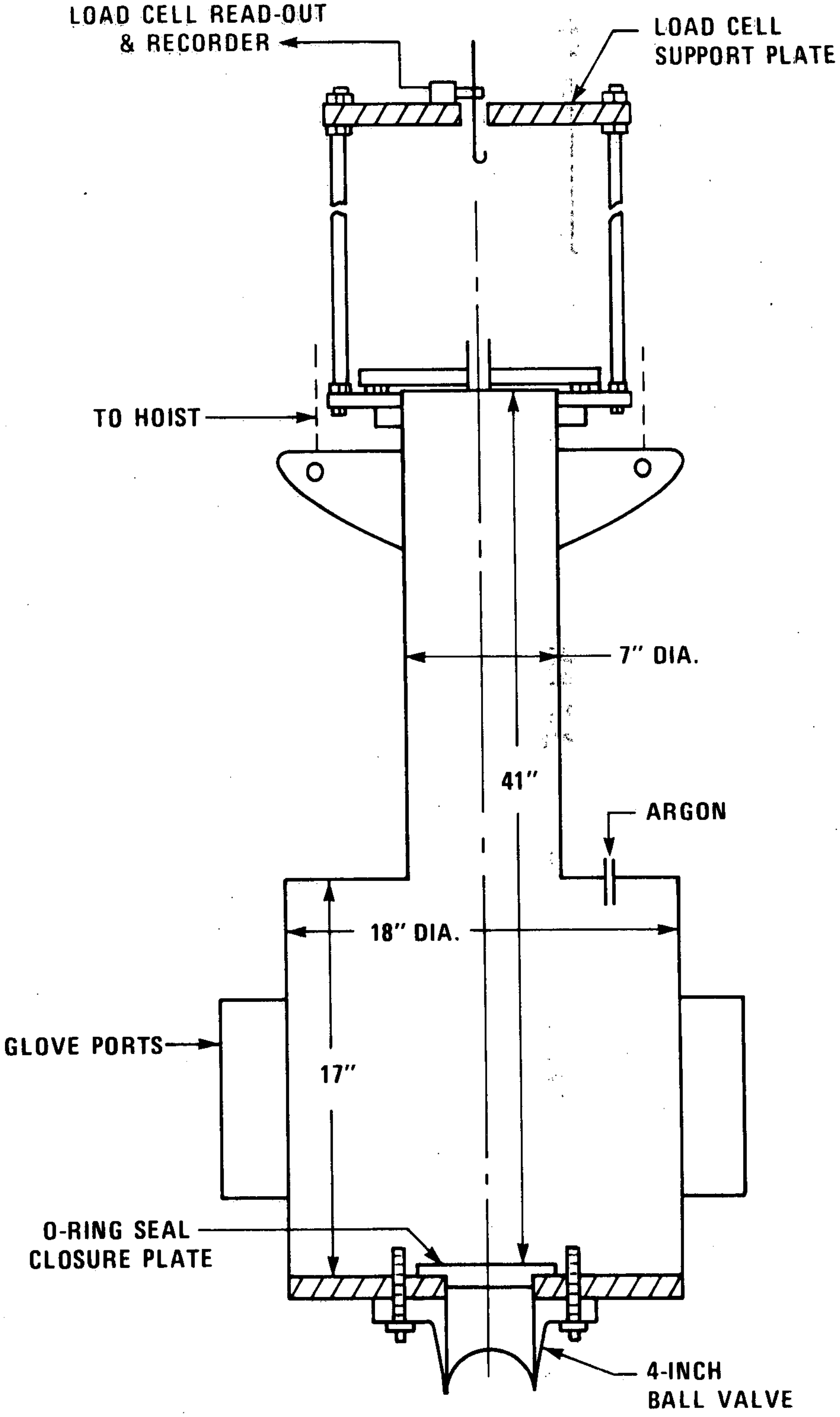

Figure 12. MFSA Transfer Vessel and Load Cell Weighing Arrangement

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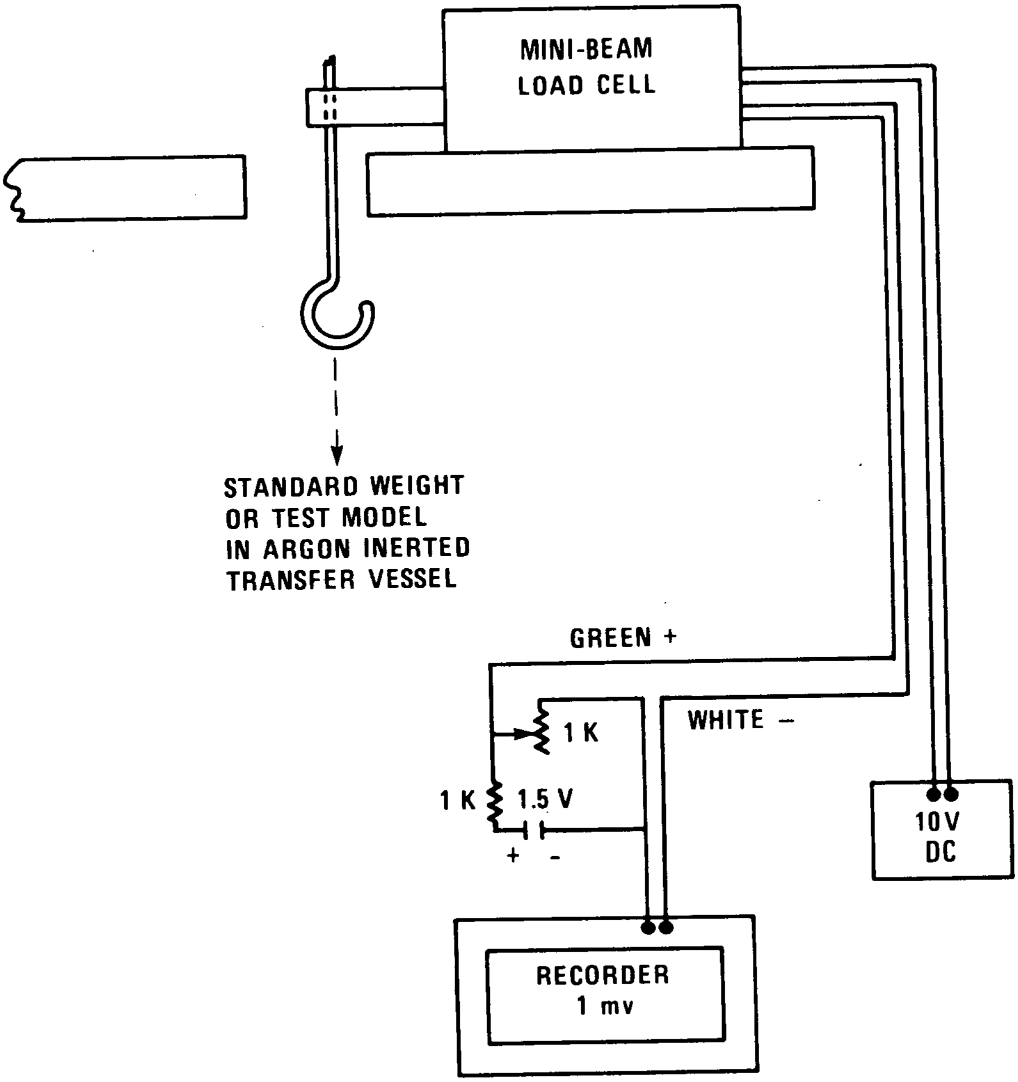

Figure 13. Load Cell System for Weighing Wetted Test Models

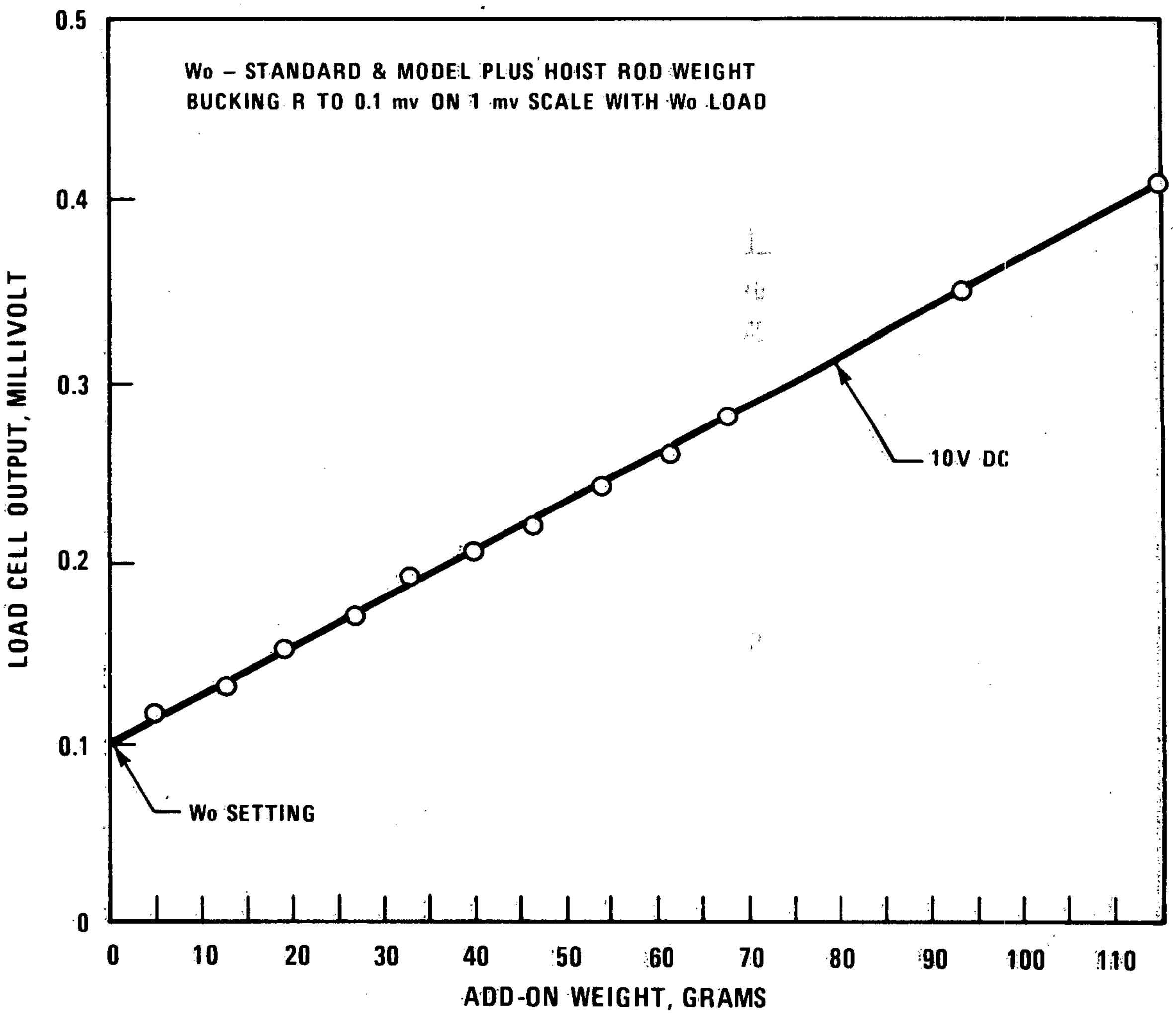

Figure 14. Calibration of MFSA Load Cell Weighing System

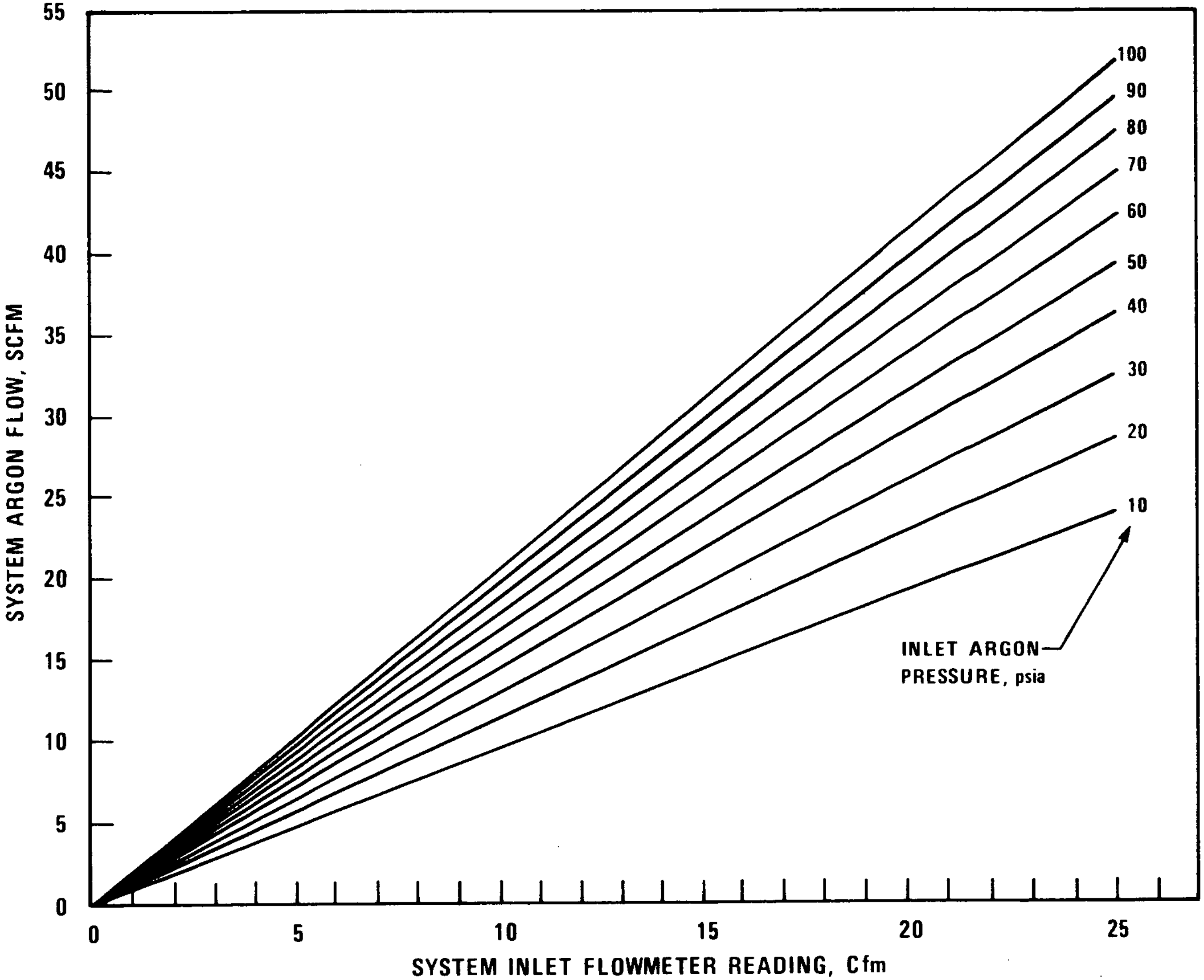

Figure 15. MFSA Inlet Rotometer Calibration for System Argon Flow

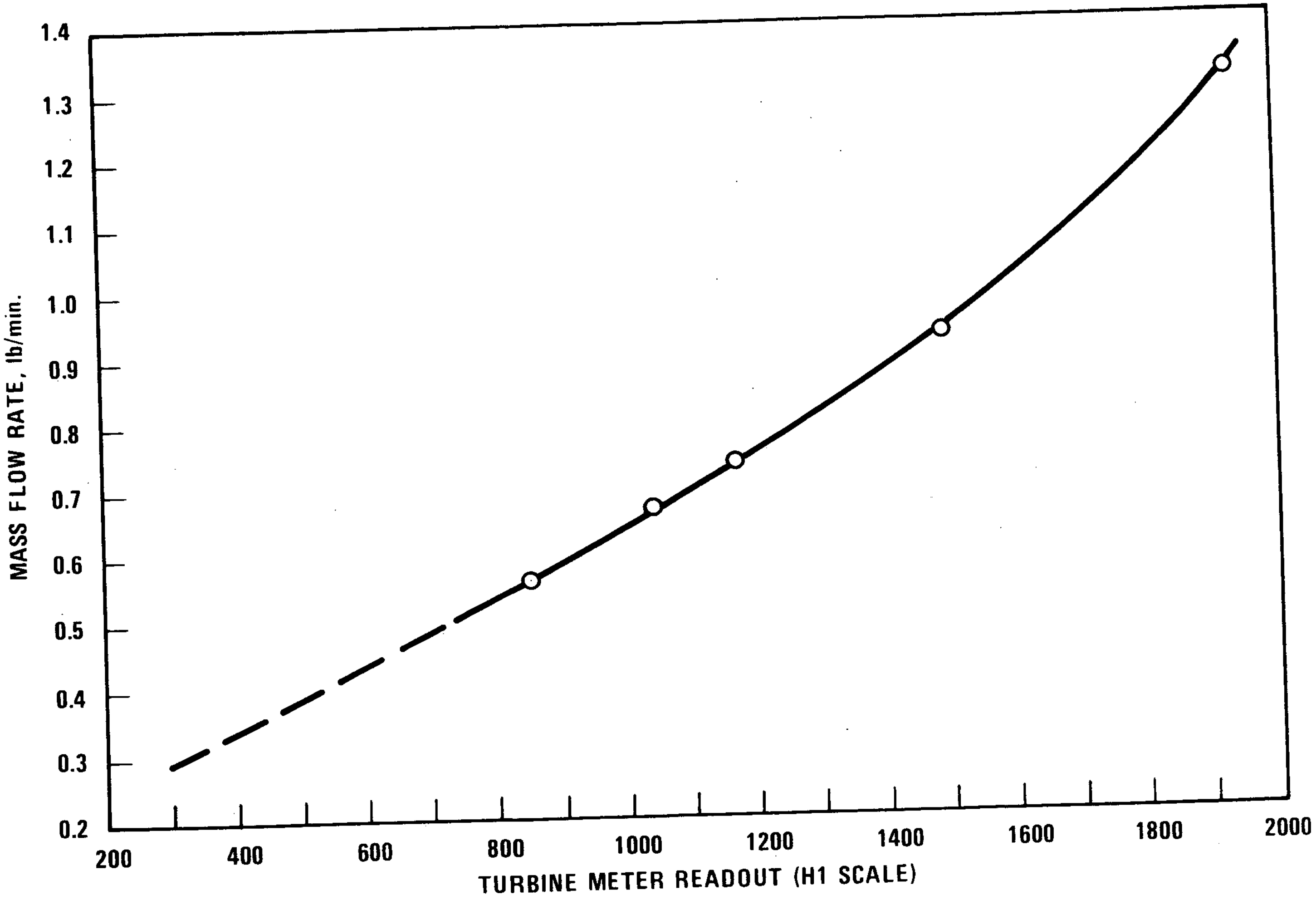

Figure 16. Turbine Meter Calibration for System Steam Flows

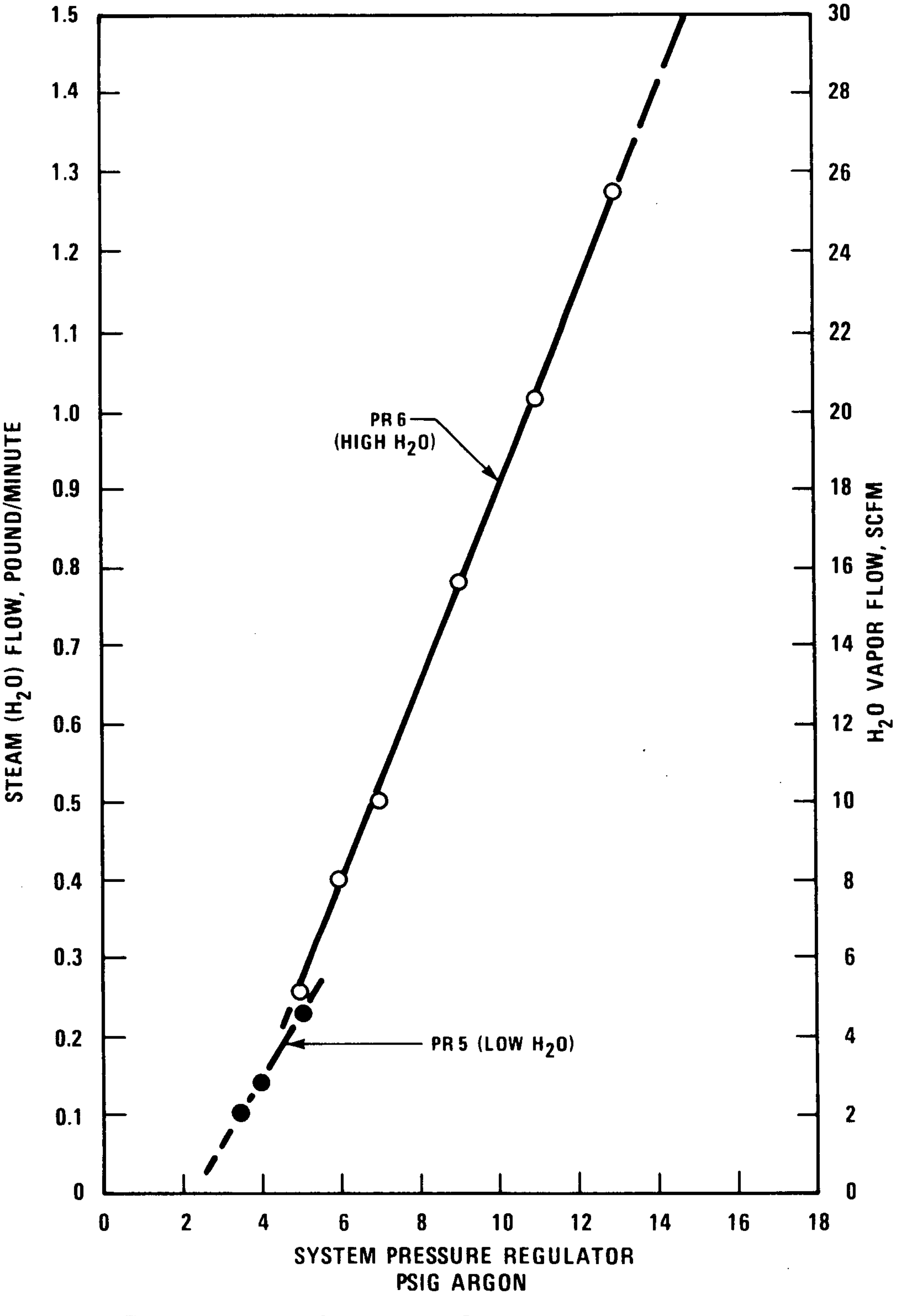

Figure 17. Inlet Steam Valve Pressure Regulator Settings for System Steam Flow

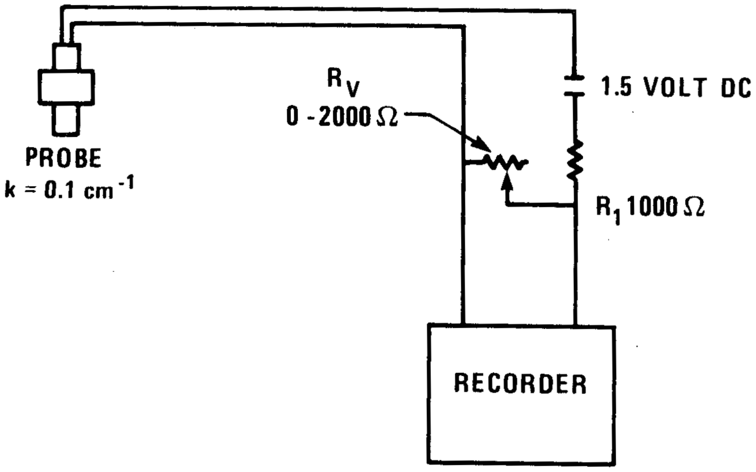

Figure 18. Effluent Resistance Probe Measuring System

concentrations up to 5 $^v/_o$. The analyzer was characteristically calibrated with a 5 $^v/_o$ hydrogen-in-argon mixture prior to each sodium removal operation.

G. Inlet piping and removal vessel trace heaters, heater controls and a multipoint temperature recorder capable of maintaining and monitoring process temperatures in the range of the target sodium removal process temperature of 300°F (149°C).

Sodium Wetting Tests (Subtask B.3)

Five (5) sodium wetting operations were performed on the development test model in the sodium wetting facility. Sodium removal process development tests were conducted on this wetted model at the conclusion of the second, third and fifth wettings. The results of sodium wetting tests are summarized in Table 4. On the basis of post wetting visual examination and model weighing results, the optimum wetting conditions were obtained during the third, fourth and fifth wetting operations at sodium immersion temperatures of 570° to 630°C (1058° to 1166°F) for immersion periods of 20.5 to 21.5 hours and sodium drain at 220° to 290°C (428° to 559°F) under argon for one (1) hour. Sodium removal was not conducted at the conclusion of the first wetting operation since the model was not wetted. Following this initial wetting, the model was reinserted for the second wetting operation. While sodium wetting appeared complete after the second wetting, some globular accumulations were noted which contributed to the higher sodium inventory measured by load cell.

A requirement of the development program was to determine the "worst case" locations, if any, in the 37-pin bundle with respect to sodium retainment in order to establish the pin bundle locations for sodium-corroded, pressurized pins in the process proof test phase of the study. For this purpose, the development test model from the fourth wetting operation was removed from the transfer vessel following wetting into an argon inerted polyethylene glove bag. The model was disassembled in this bag and examined to assess uniformity of residual sodium distribution. At this point, it was necessary to identify individual pin locations. This was accomplished by arbitrarily referencing Pin Number 1 to a file mark on the OD surface of the inlet nozzle body (see

TABLE 4
SODIUM WETTING OF DEVELOPMENT TEST MODEL

Wetting Test No.	Activity	Temperature, °C(1)	Time, Hrs.	Sodium,(2) Grams	Remarks
1	wet	420-448	20.5	∿29	incomplete wetting, some globular accumulation
	drain	205-222	1.3		
2	wet	550-560	21.7	∿47	complete wetting, globular accumulation
	drain	200-225	1.3		
3	wet	570-595	21.5	∿42	uniform wetting
	drain	235-290	1.0		
4	wet	570-600	20.5	∿40	uniform wetting
	drain	235-270	1.0		
5	wet	570-630	20.5	∿42	uniform wetting
	drain	220-290	1.0		

(1) Temperature range indicated by wetting vessel immersion thermocouples.

(2) As determined by load cell deflection of wetted model compared to deflection due to standard model weights.

Figure 19). Photographs of the sodium-wetted model at various disassembly stages are shown in Figures 20-22. Conclusions reached on sodium distribution in the wetted model were as follows:

A. Sodium film wetting appeared to be present on all model surfaces. There was no evidence of bulk sodium accumulation at the bottom of the inlet nozzle slots.

B. There was no definite radial distribution trend, however, in the axial region of highest accumulation (1-3 inches from the rail end) there appeared to be somewhat more sodium on pin and duct surfaces at the pin positions 15, 22, 28 and 33.

C. Axially, the heaviest sodium accumulations were at 1-3 inches from the rail end and were associated with wire attachments and wire-to-clad interfaces. There were lesser accumulations at axial levels of 4, 6, 8, 10, and 12 inches from the rail end, the amount appearing to decrease with distance from the rail end. Again, these latter axial accumulations were associated with wire-to-clad interfaces.

D. A continuous sodium crevice was observed at the wire-to-clad gaps for each individual pin.

E. There were some random sodium accumulations on pins with no particular axial or radial pattern, for example, a large accumulation bridging at the top of pins 37 and 36.

A report(12) describing results of the examination of the sodium-wetted model was issued to ORNL for review. On the basis of findings, a decision was made, to which ORNL concurred, to locate the six (6) sodium-corroded pins at model pin bundle locations of 19, 20, 21, 22, 27 and 28 in the Process Proof Test (Figure 19). It was also recommended (and accepted) to include pressurized pins from the development test model at pin bundle locations of 26, 32, 33 and 37 in order to completely represent the hexagonal pattern.

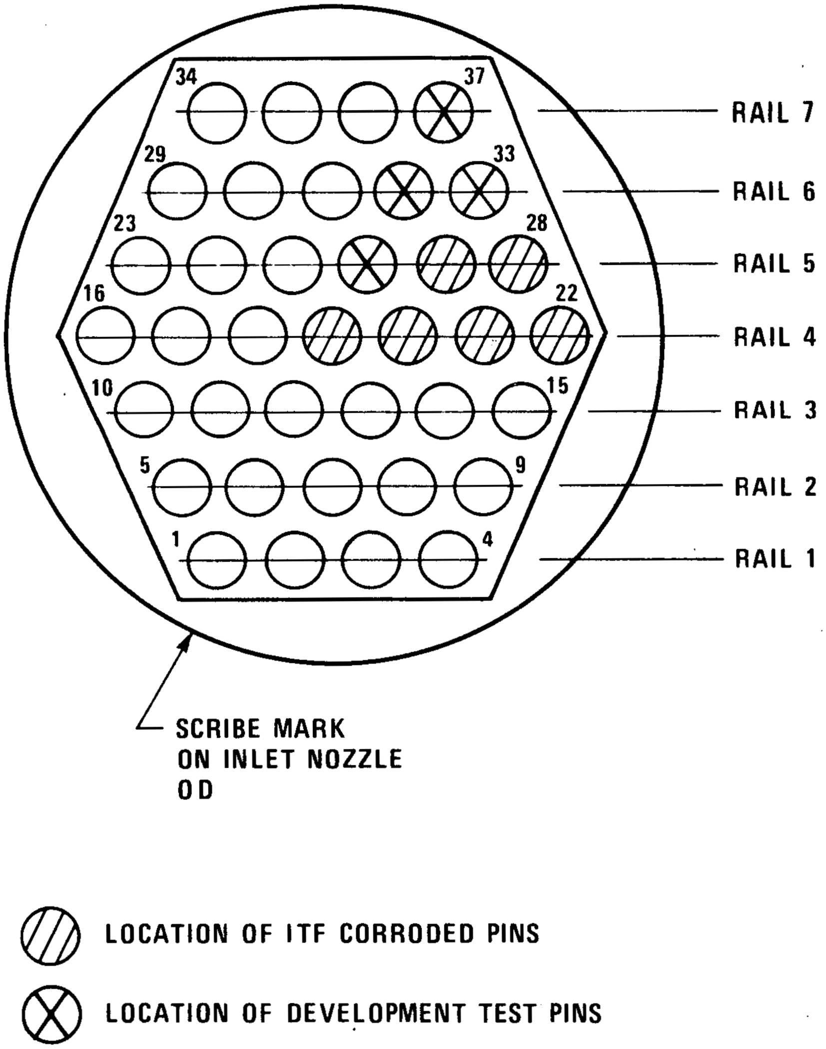

Figure 19. Location of Corroded Pins in MFSA Proof Test

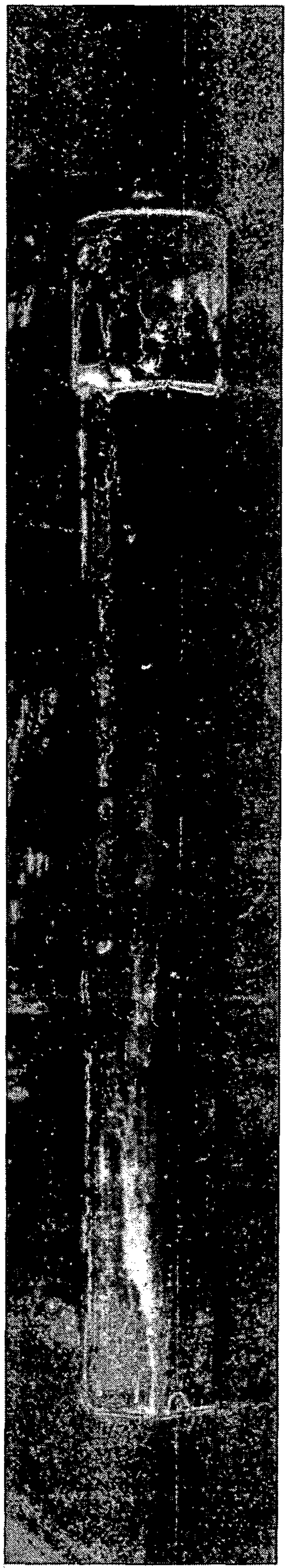

Figure 20. MFSA Handling Socket-Duct After Fourth Sodium Wetting

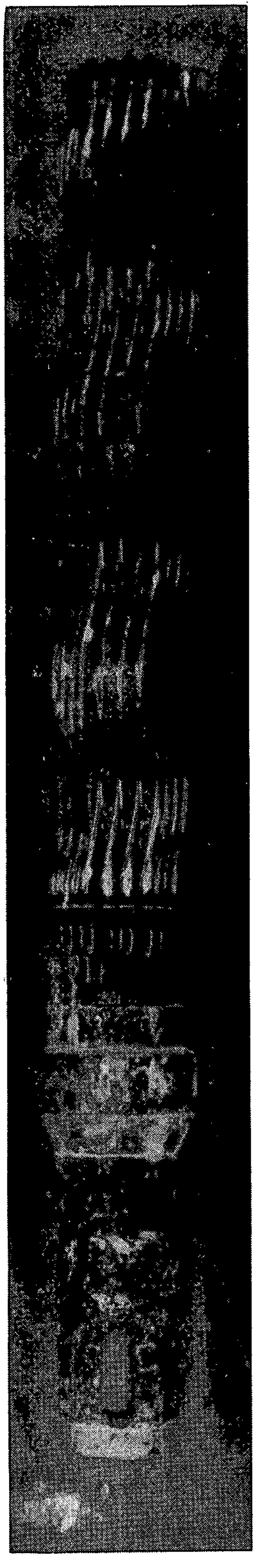

Figure 21. MFSA Inlet Nozzle-Pin Bundle After Fourth Sodium Wetting. Pins 1-4 Are Up

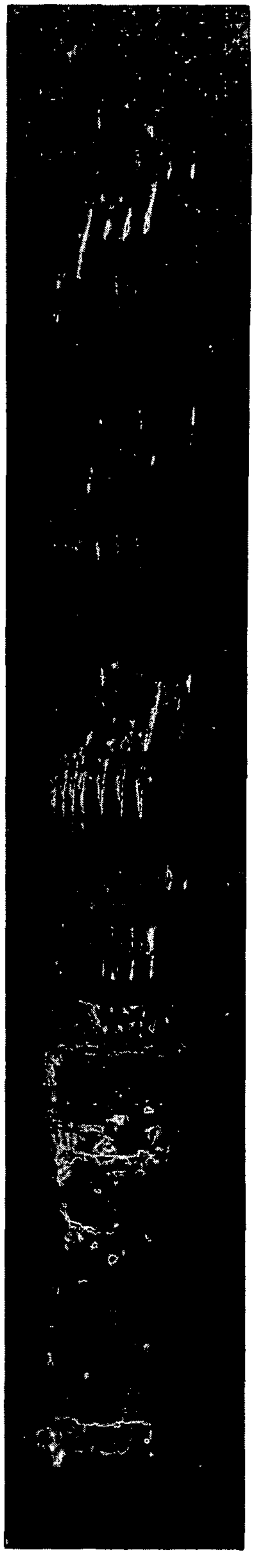

Figure 22. MFSA Inlet Nozzle-Pin Bundle After Fourth Sodium Wetting. Pins 34-37 Are Up

Test Model Flow Characterization (Subtask B.3)

The process development tests were conducted in a sodium removal vessel which had a removable orifice plate bolted to an upper support ring machined as an integral part of the vessel wall. Flow gaps formed between the machined ID of the plate and the outer surface of the model handling socket controlled the division of argon-water vapor flow to the internal and external surfaces of the test model during the sodium removal process.

The purpose of the flow-characterization test was to establish the orifice plate flow-gap size which would produce adequate gas flow conditions on internal and external surfaces of the test model. The desirable hydraulic condition can be assumed to result from flows producing equivalent Reynolds numbers, but a lower Reynolds number external to the fuel subassembly would be acceptable due to the lower expected sodium loads on the external surfaces.

A. $Re^i = Re^e$
B. $ve/vi = De^i/De^e = (Fe/Ae)\ (Ai/Fi)$
C. $Fe/Fi = a$, where $a = (De^i/De^e)\ (Ae/Ai)$
D. $Ft = Fe + Fi$
E. $Fi/Ft = (a+1)^{-1}$.

Re^e = Reynolds No., external flow
Re^i = Reynolds No., internal flow
De^i = Equivalent diameter, internal
De^e = Equivalent diameter, external
ve, vi = flow velocity, external and internal
Ft = Total volumetric gas flow
Fe = Volumetric gas flow, external
Fi = Volumetric gas flow, internal
Ae = flow cross-sectional area, external
Ai = flow cross-sectional area, internal

From test model data in Appendix A ($De^i = 0.271$ cm, $Ai = 0.006$ ft^2) and from annular gap measurement between the test model OD and the removal vessel

ID (De^e = 3.81 cm, Ae = 0.34 ft^2) the desired flow velocity ratio Fi/Ft was calculated as approximately 0.71.

The basis of the flow characterization test then was to measure flows internal to the model with various pre-machined orifice plates in place and at various total flows to the model. To do this, a 2-inch pipe with a 4-inch plexiglas flange was sealed to the handling socket of the model while in place in the sodium removal vessel. This arrangement permitted measurement of pressure differential (by mercury manometer) between flows external and internal to model and flows through the model by another calibrated rotameter mounted on the 2-inch pipe vent. With various calibrated inlet system argon flows, the flows internal to the model were measured and average flow ratios determined for various orifice plate annular flow gaps:

Plate	Annular gap, $in.^2$	System Flow, SCFM	Average Flow Ratios, Model Flow/System Flow
None	1.25	26	0.49
No. 1	0.46	26	0.53
No. 2	0.36	26 - 41	0.60 - 0.61
No. 3	0.26	26 - 41	0.75 - 0.76

On the basis of this data, orifice plate No. 3 was selected for use in development tests.

Process Development Tests (Subtask B.3)

Idealized analyses of sodium removal from the 37-pin test model based on hydraulic and mass transfer similitude with a full scale CRBR fuel subassembly (Appendix A.5) indicate that, to meet a target reprocessing time of 60 minutes (or less) for a full scale assembly, sodium removal from the test model must be demonstrated to be adequate within a total water vapor-argon reaction time of about 5 minutes and a total water rinse time of about 2 minutes. Additional restraints based on Sodium Removal System(1) decay heat control concepts require that test model sodium removal be performed at 300°F (149°C). Decay heat analyses (Appendix A.2) for a full scale CRBR subassembly indicate that a total internal nitrogen flow of about 220 SCFM would be required for this level of temperature control. Considering mass transfer similitudes (Appendix A.5), minimum internal (argon) gas flows and minimum total gas flows to the test model would be about 30 and 40 SCFM respectively with the use of the orifice control plate (Fi/Ft = 0.75) described previously. Another desirable goal of the development tests was to demonstrate that adequate caustic (sodium) removal could be obtained with a generation of minimum amounts of waste rinse water.

Three process development tests were performed at the conclusion of the second, third and fifth sodium wetting operations on the development test model. The results of these tests are given in Table 5 and Figures 23 to 26. End points given in Table 5 for the completion of sodium reaction in the water vapor phase (water vapor sodium reaction time) and for removal of caustic in the water rinse phase (water rinse cleaning time) were selected as those elapsed times when effluent hydrogen concentrations and effluent sodium hydroxide concentrations were $\leq$100 ppm and $\leq$4 ppm respectively from hydrogen analyzer and resistance probe traces reproduced in Figures 23 to 26.

At the conclusion of the first sodium removal process development test, it was deemed advisable to attempt to eliminate the low water vapor injection phase and thus accelerate sodium reaction and shorten vapor injection time. This was considered possible on the basis that the first test occurred without thermal transients and without significant caustic corrosion effects even at the high process temperature of 300°F. For this purpose, the two additional tests were run at higher water vapor injection and water rinse rates as shown in Table 5. There were no thermal excursions noted in the three tests, the sodium reaction appearing to run smoothly and quietly. As measured by immersion thermocouple, the water vapor phase operations were carried out at model temperatures ranging from 145°-155°C (293°-311°F). Deionized rinse water at ambient temperature accompanied by a low argon flow (∿2 SCFM) was pumped to the model immediately following termination of the water vapor injection in a straight-through flush. Typically, water temperatures as measured by the immersion thermocouple rose quickly to about 100°C and then dropped to about 30° - 40°C during the rinse cycle.

The models were disassembled and examined after each of the development tests and the model parts rinsed with deionized water for residual sodium analysis by a sodium ion probe. No physical damage, pitting or cracking was observed in pin cladding, welds or model hardware at the conclusion of all three tests. A light gray-to-tan discoloration was observed on cladding and hardware believed to be the result of light caustic corrosion accumulating through the three tests. Photographs taken of the model following each of the tests are given in Figures 27 to 29.

Water rinse-residual sodium correlations in Table 5 indicate that variable rinse volume flow conditions produced similar results with respect to the amount of sodium equivalent remaining on the model following water rinse. It should be noted that the residual sodium results include crevice sodium in atypical locations of the eye bolt and duct screw threads which would not be present on a full scale subassembly. These latter crevice inventories were estimated to range from 0.5 to 0.3 grams of sodium indicating that most (∿99%) of the typical sodium and sodium hydroxide present on model surfaces was reacted and removed by the water vapor and water rinse treatments. It was concluded from the development test results that 1) direct water vapor injection rates of 50 v/o or greater expedite sodium reaction and do not cause cladding. damage, 2) increases in total flow while maintaining 50 v/o or greater water vapor content tend to shorten vapor injection time, and 3) higher water rinse flows tend to shorten cleaning time as indicated by resistance probe response. On the basis of these conclusions, the optimum process conditions for the Proof Test Model were recommended (and accepted by ORNL) to be those for which the model Sodium Removal System has maximum measurable capacity, i.e., 26 SCFM argon, 26 SCFM water vapor and a 4.3 gpm water rinse.

SODIUM REMOVAL PROCESS PROOF TEST (TASK WBS C)

The objectives of Task C as specified in the Process Proof Test Plan(13) were as follows:

A. Perform sodium corrosion exposures on six (6) model pins to produce spent fuel cladding conditions.

TABLE 5

RESULTS OF PROCESS DEVELOPMENT TESTS

	Water Vapor-Argon (145-155C)			Water Rinse (Ambient)			
Test No.(1)	Total SCFM	v/o H_2O	WVSRT, min.(2)	GPM	Time, min.(3)	WRCT, min.(4)	Residual Na,mg
1 (47g)	40	5	incomplete	1.3	12	not determined	736
	40	50	8.2				
2 (42g)	45.5	52	5.4	4.3	7	1.4	629
3 (42g)	40	65	5.0	3.3	6	1.5	683

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(1) Sodium inventory at wetting by load cell weighing.

(2) Water Vapor Sodium Reaction Time based on effluent hydrogen concentration ≤ 100 ppm.

(3) Time to deionized water level by resistance probe. Probe not operative on Test 1 and rinse performed to pH 6.5.

(4) Water Rinse Cleaning Time based on effluent resistance probe indicating ≤ 4 ppm NaOH concentration level.

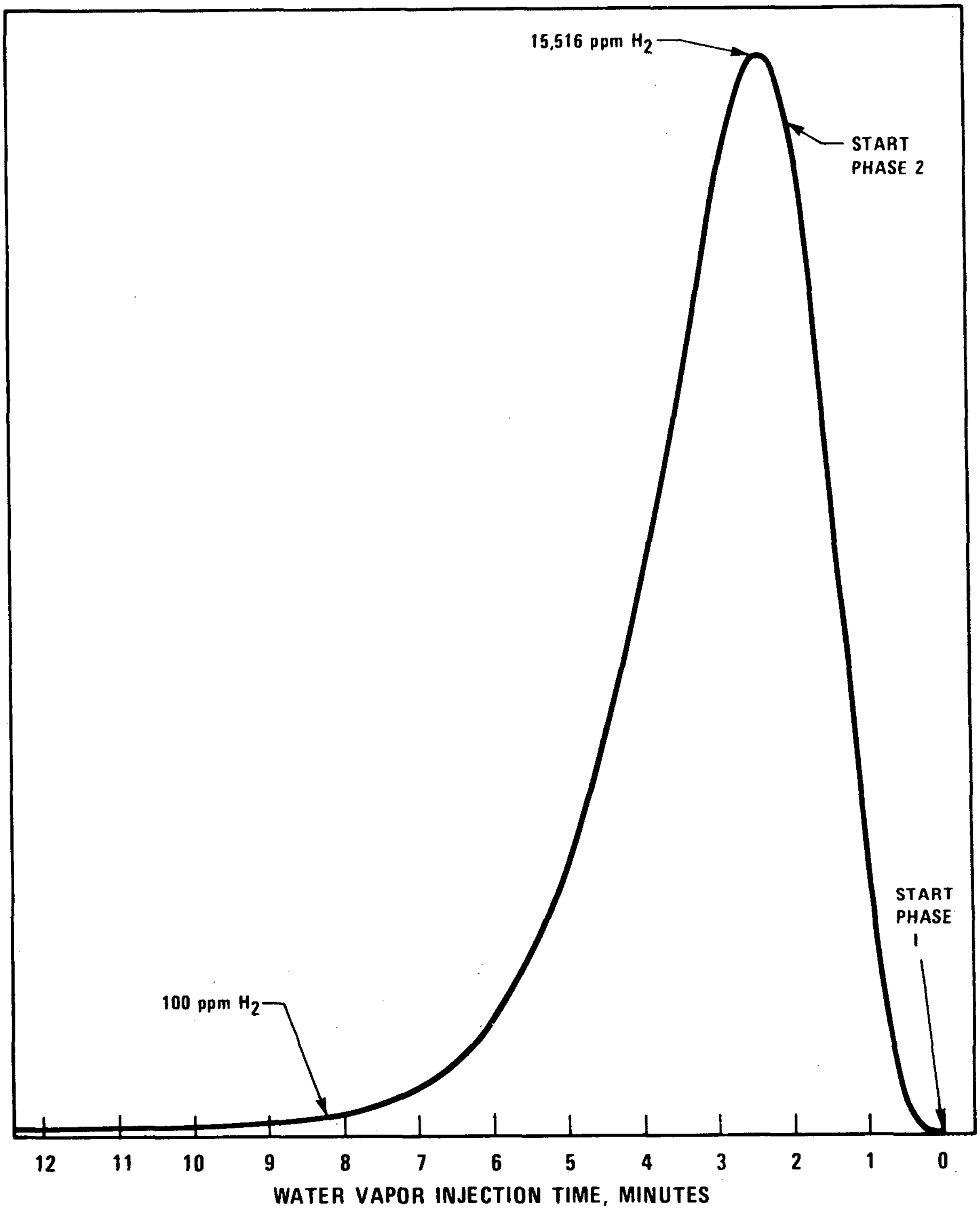

Figure 23. Effluent Hydrogen Concentration Profile for Development Test No. 1

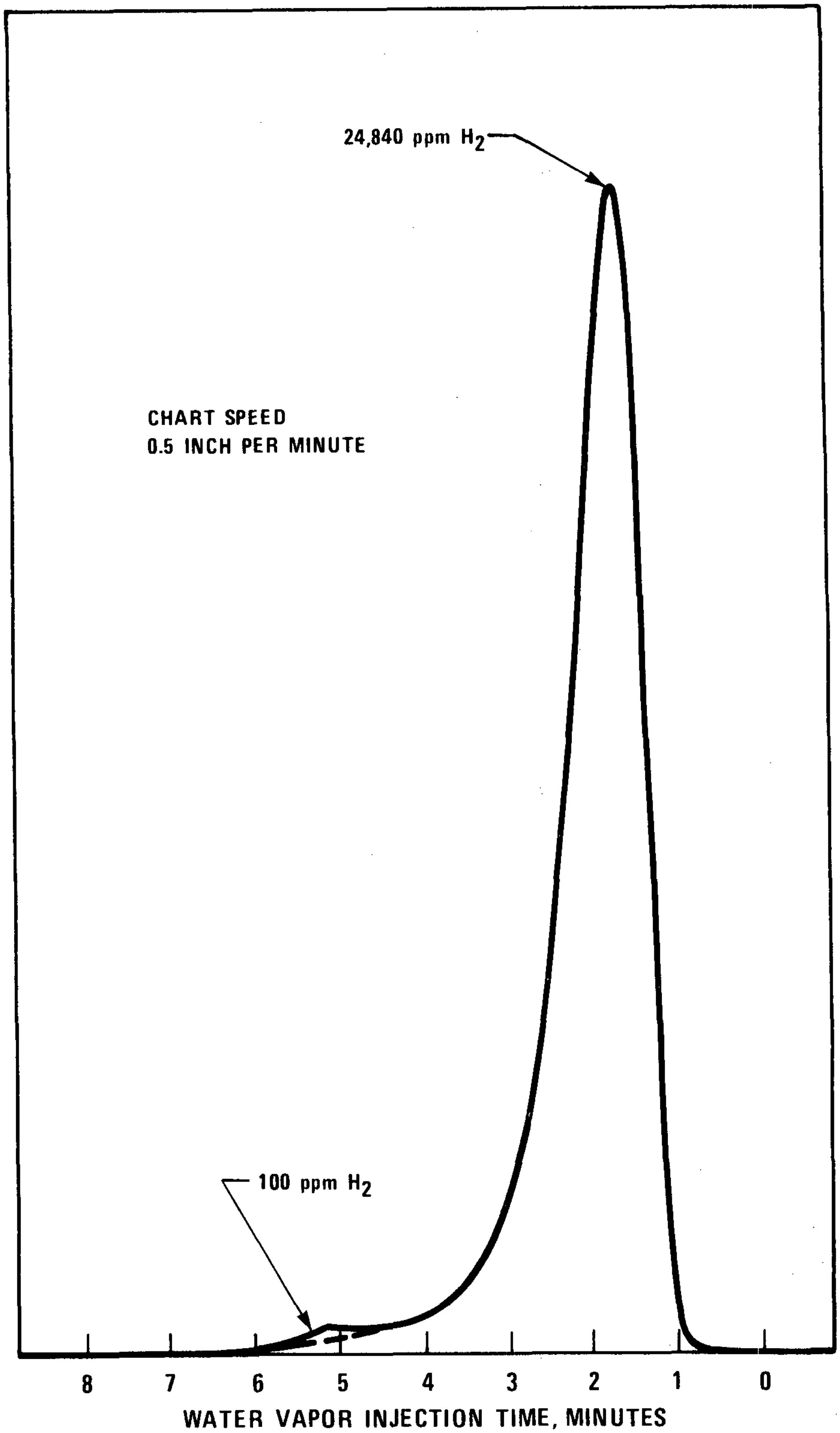

Figure 24. Effluent Hydrogen Concentration Profile for Development Test No. 2

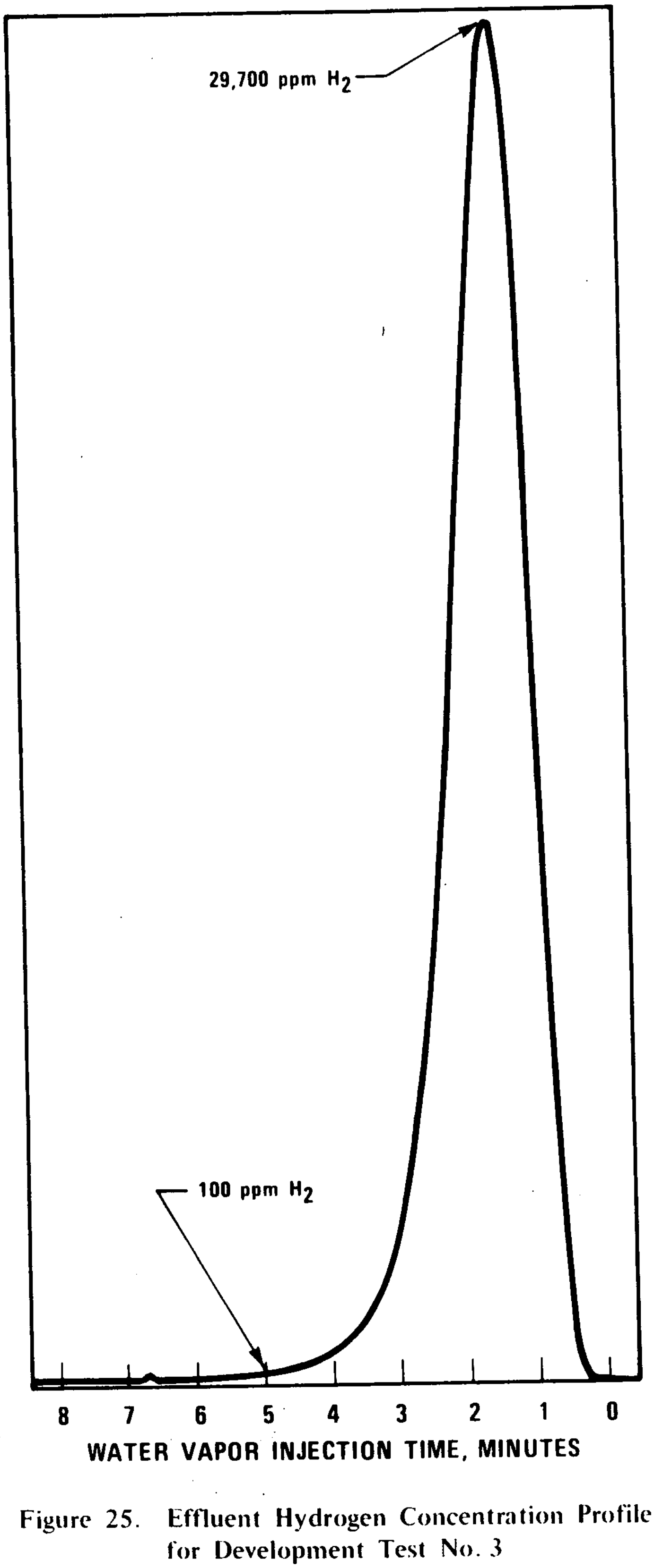

Figure 25. Effluent Hydrogen Concentration Profile for Development Test No. 3

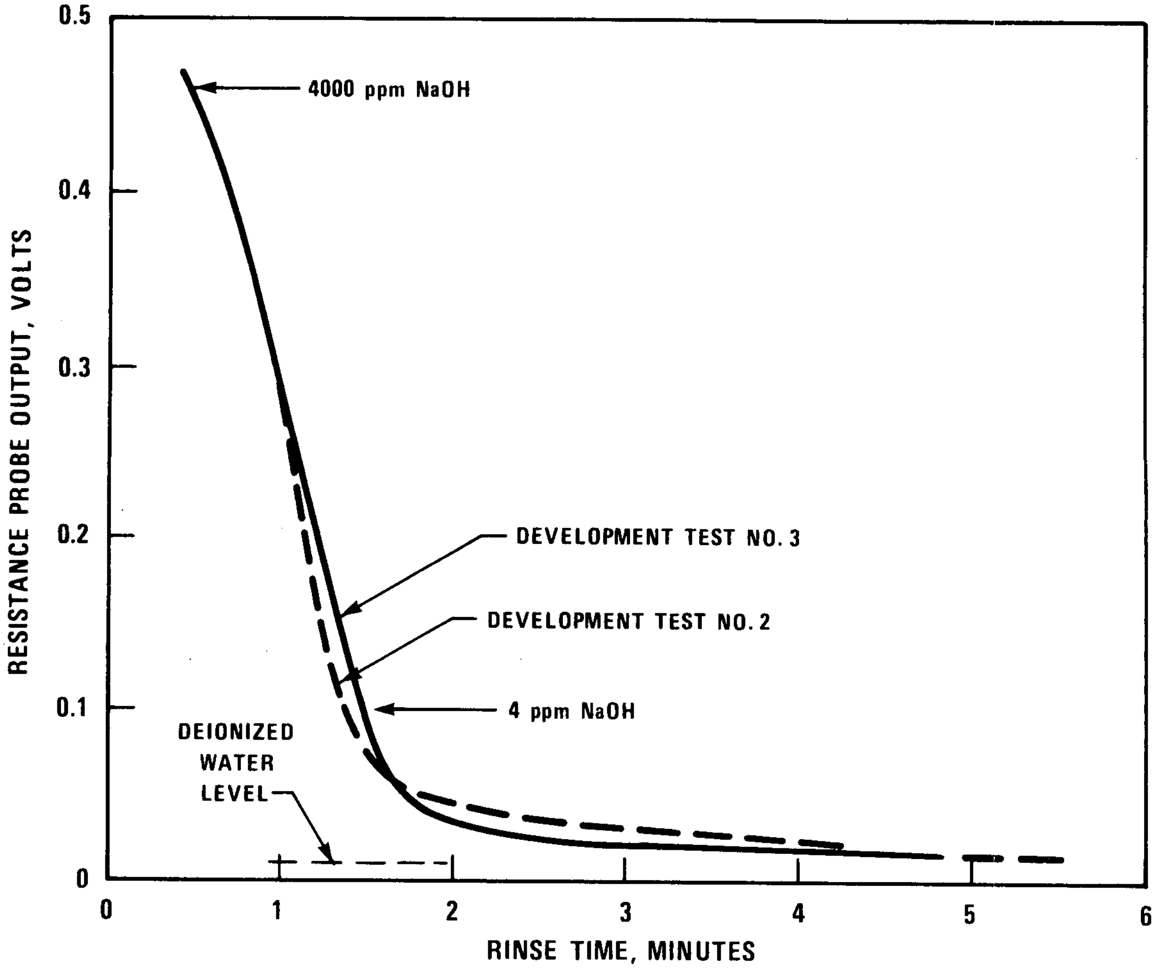

Figure 26. Effluent Resistance Probe Profiles for Development Test Water Rinse

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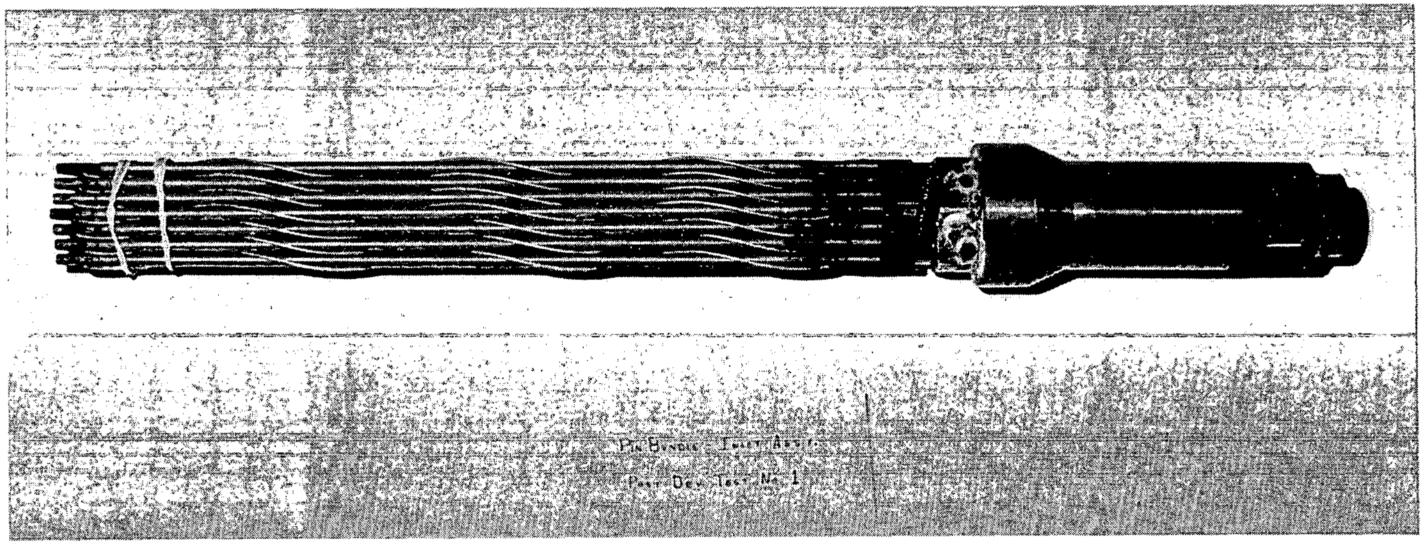

Figure 27. MFSA After Development Test No. 1

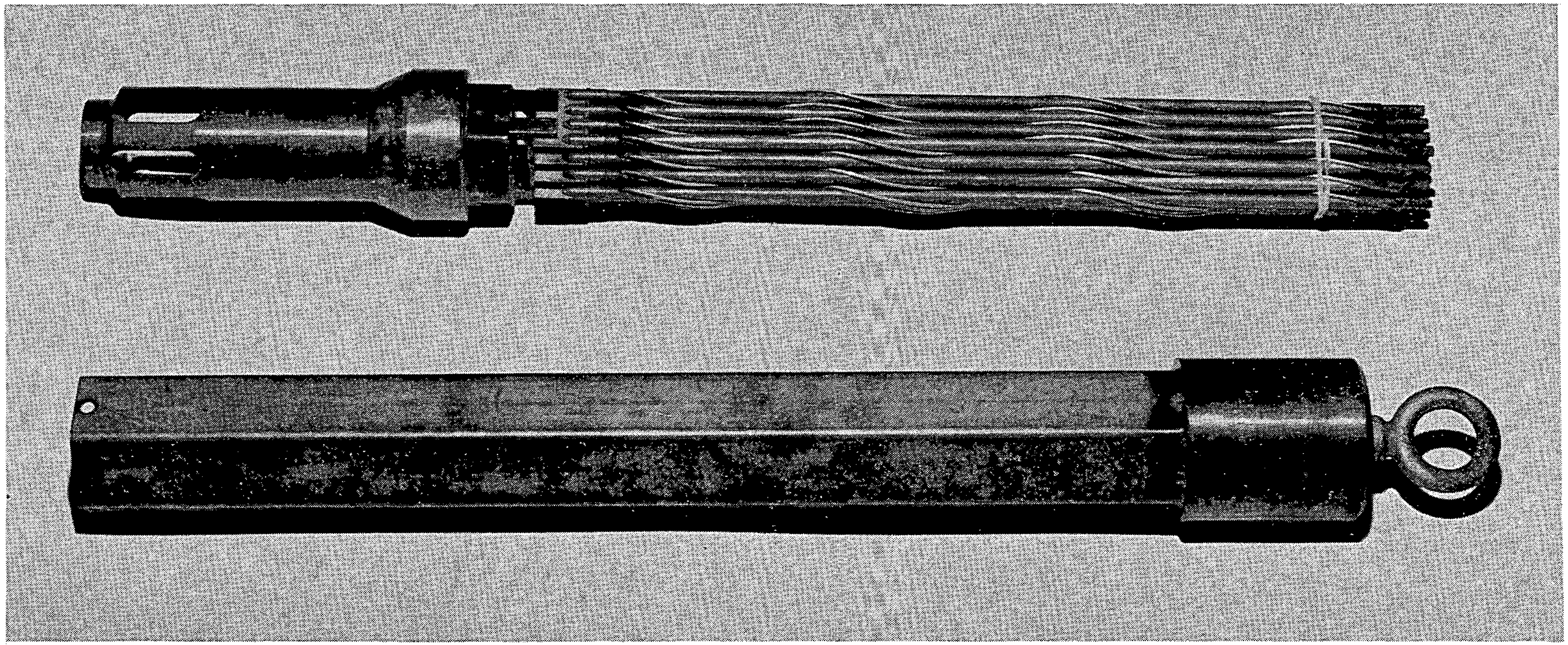

Figure 28. MFSA After Development Test No. 2

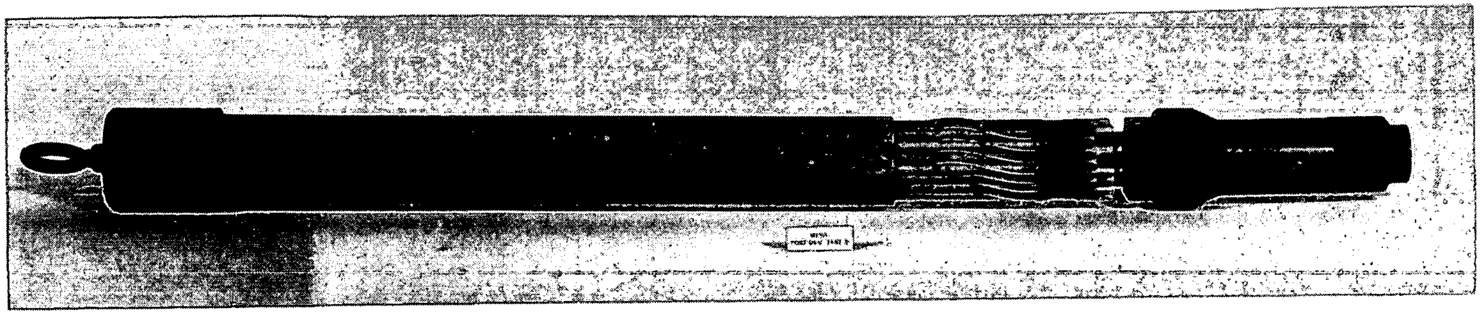

Figure 29. MFSA After Development Test No. 3

B. Perform sodium wetting and sodium removal on the Proof Test Model containing sodium-corroded and pressurized pins at the optimum process parameters recommended in the development test phase.

C. Perform a six-month water storage test of the Proof Test Model at the conclusion of sodium removal under water chemistry conditions specified by ORNL.

D. Examine and evaluate the corrosion performance of the Proof Test Model following water exposure.

The results from activities conducted under Task C to accomplish these objectives are summarized in this section.

Test Pin Sodium Corrosion (Subtask C.2, C.3)

Six wire-wrapped model fuel pins were exposed to flowing sodium at 650°C (1202°F) for 2000 hours in the W-ARD Interstitial Transfer Facility (ITF) in order to produce a ferrite surface layer to simulate the condition of spent fuel cladding. Two high temperature, 2000 hour tests with three pins and metallographic travelers in each test were conducted in the isothermal hot-leg of this facility. A report(14) describing details of the exposure and complete metallurgical and mass loss characterization was issued. The results, as summarized in Tables 6 and 7 and in Figure 30, show that the objective of the exposure was met and that a thin ferrite layer was formed on the surface of the sodium-exposed model pins. A photograph of corroded pins from Facility run 17 is given in Figure 31.

Process Proof Test (Subtask C.4)

The assembly requirements for the Proof Test model are given in Table 8. The sodium-corroded pins were cleaned of residual sodium by alcohol immersion to preclude caustic corrosion effects. Argon pressurization of the sodium-corroded and four selected development test pins were accomplished in the W-ARD Fabrication Laboratory utilizing the pressurization system shown in Figure 32. In this system, cryogenic argon was introduced through a stainless capillary welded in the top end cap of the pins, the pressure stabilized to about 350 psig, the capillary pinched shut and then welded. A spare development pin was also pressurized and sent to ARD Analytical Laboratory for measurement of pin pressure level. The results, utilizing a pin-puncture device and a calibrated gas volume, indicated a pin pressure of 360 psig at ambient conditions (19.4°C). All of the model pins in the Proof Test assembly were weighed on a Mettler balance before assembly. A photograph of the Proof Test model is shown in Figure 33.

Following assembly of the Proof Test model, sodium wetting was performed in the Model Sodium Wetting Facility. The parameter of this sixth wetting operation are summarized in Table 9. As with previous development test wettings in this temperature range, uniform wetting of the model external surfaces was obtained and a similar sodium inventory (43 grams) was obtained by load cell weighing.

At the conclusion of wetting, the Proof Test model was transferred under argon into the Model Sodium Removal Facility test vessel. The sodium removal process proof test was then performed at the maximum argon-water vapor injection and water rinse flow test parameters previously specified by the development tests. A summary of test results are given in Table 10. The effluent hydrogen concentration profile (Figure 34) and the effluent resistance probe data (Figure 35) indicated that completion of sodium reaction and of cleaning by water rinse was essentially complete in 4.2 and 1.3 minutes respectively. A photograph of the external surface of the model following sodium removal is shown in Figure 36.

Water Storage Test (Subtask C.5)

In concurrence with ORNL water pool chemistry and storage requirements shown in Table 11, the water bath facility shown schematically in Figure 37 was designed and installed in the W-ARD Sodium Technology Laboratory; The Proof Test model, following sodium removal, was immersed in the deionized water of this bath on January 14, 1981 and withdrawn on July 21, 1981 after immersion for 4512 hours (188 days).

A tabulated history of temperature, conductance and analytical sampling for this period is given in Table 12. A total of 29 drain operations were performed to maintain conductance values in the range of 4-12 micromhos/cm (see footnote* below). Forty-eight (48) 100 cc samples were taken to monitor chloride, sodium and pH. Eight (8) water samples were also taken for chloride/fluoride analysis (Dionex) and Fe, Cr, Ni analysis (flameless atomic adsorption) at start, 16 days into and at the end of the water testing. The model bath temperature was continuously monitored. Based on these recordings the immersed model temperature (measured at model mid-point) was in the range 180° ± 5°F (82° ± 3°C) for 4365 hours, in the range 160° - 180°F (71° - 82°C) for about 58 hours due to the 29 drain operations and in the range 185° - 195°F (85° - 90.5°C) for approximately 100 hours during unattended operation. On a sampling basis, pH values were observed to decay downward from 11 to 7 during the initial 10 days of immersion and then remained at about 6 ± 0.5 units for the remainder of the test. Initial (7-8 days) sodium ion concentration and specific conductance values were high due to the dissolution of residual sodium and/or caustic. With the known water both volume, a residual sodium equivalent of about 335 mg was calculated from the sodium ion data. It should be noted that the eye hook crevice on the Proof Test model was cleaned of sodium by alcohol prior to water immersion. Results of chloride, fluoride, iron, chromium and nickel analyses by Dionex and flamless atomic adsorption are shown in Table 13. The course of periodic sodium and chloride ion probe analyses conducted on water bath samples is given in Table 12.

Post Test Examinations (Subtask C.6)

After withdrawal from the water bath, the Proof Test model was air-dried and disassembled. Other than rust films, no physical or corrosion cracking or pitting damage was noted on the hardware, pin claddings or welds. Color

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*The specific conductance requirement in Table 11 is ≤5 micromho/cm at room temperature. For ions of interest (NaOH) the ratio of conductance at 100°C versus 18°C is about 2.7. The both value can be 13-14 micromho/cm.

photographs of the water tested model and pins are shown in Figures 38 and 39. The pressurized pins from the Interstitial Transfer Facility sodium corrosion test and from the development test model appeared to have somewhat heavier corrosion and rust films. The least corroded cladding appeared to be associated with the as-fabricated pins.

Post water bath pressure measurements on the proof test pressurized pins in Table 14 indicates no pressure loss had occurred. A gain in pressure was indicated which is believed to be due to out-gassing of the ceramic pellets contained in the pins.

The Proof Test pin weight changes are given in Table 15. Nominal changes were observed on the as-fabricated pins while the pressurized pins showed weight losses at a somewhat higher level.

Metallographic examinations were conducted on cladding samples from six (6) selected pins from the Proof Test model. The microstructure of transverse sections of cladding from proof test pins and untested clad stock are shown in Figures 40 and 41. Typical for pressurized, sodium-corroded, development test and as-fabricated proof test pins are given. As can be seen from Figures 30 and 41b, the ferrite layer produced in the pre-sodium-corroded proof test pins was unaffected by the sodium removal and 6-month water storage tests. As in previous smal scale cladding studies,(2,3) cladding microstructures of all types of proof test pins showed little effect of the 300°F sodium removal and 82°C water storage. Characteristically, massive intragranular carbide precipitation due to severe cold work again was observed in the proof test pin claddings which contributed to the corrosion resistance and the observed obsence of inter/intragranular attack and localized pitting.

TABLE 6

SODIUM EXPOSURE CONDITIONS FOR MODEL PINS(a)

Run	Range, Cold Trap Temperature, °C	Exposure(b) Time, hrs.	Range(c) Oxygen, ppm
17	140.5-137.7	457-1720	1.6-2.1(6.0)
18	137.7-132.2	408-1939	1.4-2.3(7.4)

(a) Nominal ITF isothermal leg conditions were:

Sodium temperature - 650°C (1202°F)
Sodium velocity - 3 meters per second

(b) Time frame of pin exposure (total 2000 hrs.) for which cold trap and oxygen data given.

(c) Concentration of oxygen in sodium by vanadium wire equilibrium method. Values in (x) are initial start-up values where O_2 levels are high due to loop inactivity. Average of O_2 concentration for both runs taken as 1.85 ppm.

TABLE 7

CORROSION RESULTS FOR METALLOGRAPHIC TRAVELERS INCLUDED IN INTERSTITIAL TRANSFER FACILITY MODEL PIN EXPOSURE TESTS[(a)]

Run	Traveler Test Position	Corrosion[(b)] Rate, mg/dm^2-year	Ferrite Thickness, μm	Surface Composition (EDS), %[(c)]					
				Fe	Cr	Ni	Mo	Mn	Si
17	Bottom	611	∿3	85.9	8.7	1.6	3.9	ND	ND
	Top	130	∿1	71.3	14.8	8.3	4.5	0.9	0.2
18	Bottom	807	∿3	87.1	8.4	1.3	3.3	ND	ND
	Top	64	∿1	74.4	13.8	7.2	3.6	1.0	ND

(a) 1-inch long, as-received, Type 316, 20% CW, cladding samples included at top and bottom (sodium inlet) of each 3-pin sodium corrosion test train.

(b) Based on weight changes of traveler specimens and dimensions.

(c) Energy dispersive spectrometry micrographs revealed micron-sized nodes rich in Fe and Mo on surface of travelers, characteristic of the early stages of T316 SS corrosion.

ND - element not detected.

TABLE 8
PROOF TEST MODEL ASSEMBLY REQUIREMENTS

1. Assembly Document

Westinghouse W-ARD Work Plan No. 4174, "Procurement, Fabrication and Assembly of Hardware for 37 Pin Simulated LMFBR Fuel Subassemblies for Sodium Removal Process Development," Rev. 0, 11/20/79.

2. Pin Bundle Make-up (all pins pre-weighed)

As-fabricated pins	27
Sodium-corroded pins	6
Corroded Development pins	4
Total pins	37

3. Corroded Pin Bundle Location

6, Sodium corroded	19, 20, 21, 22, 27, 28*
4, Corroded Development	26, 32, 33, 37

4. Corroded Pin Pressurization

Pressurizing gas	Cryogenic argon
Pressure level	350 psig
Pre-test condition	Sealed, leak-tight
Post-test	Measure pressure at conclusion of water test

---

*Pin bundle location number based on scribe mark on inlet nozzle at point adjacent to the rail end of pin No. 1.

TABLE 9
SODIUM WETTING OF PROOF TEST MODEL

	Wetting	Draining
Temperature, C	585-620	260-270
Hours	22.0	1.0
Sodium Weight, g (load cell)	43	

TABLE 10

RESULTS OF PROCESS PROOF TEST SODIUM REMOVAL

- Water Vapor Phase

Total Gas Flow, SCFM	52
v/o H_2O vapor	50
Sodium Reaction time, Min. (WVSRT)	4.2

- Water Rinse Phase

Water Flow, GPM	4.3
Time, deionized water level	5.0 min.
Time, 4 ppm NaOH level (WRCT)	1.3 min.

TABLE 11

WATER STORAGE REQUIREMENTS FOR PROOF TEST MODEL

- Full length, vertical immersion
- Low water flow internal and external to model
- Six-month storage of model under the following water control conditions:

Temperature	82° ± 1°C
Chloride ion	≤0.2 ppm
pH	7.0 ±1
Spec. Conductance	≤5 micromhos/cm
O_2 content	saturated at 82°C

TABLE 12
WATER BATH HISTORY FOR PROCESS PROOF TEST

Date-Hr.	Operation	Sample	Micromho/cm	Temp °F	pH	Na	ppm Cl^-
1-13-1333	Bath Fill	1C,2C	2.4	176	--	--	--
1-14-080	Sample	1L	3.8	180	6.2	<.04	<.01
-1040	"Model in"	--	--	--	--	--	--
-1340	Drain 1	3C,4C/2L	500	176	10.8	34	0.069
-1400	Check	--	37	167	--	--	--
-1555	"	--	79	173	--	--	--
1-15-1035	Drain 2	3L	537	180	11.1	32	--
-1605	Check	--	115	176	--	--	--
1-16-0835	Drain 3	4L	158	178	10.4	10.4	--
1-19-0807	Check	--	104	179	--	--	--
-0825	Drain 4	5L	"	"	10.1	7.6	--
-1630	Check		27.5	180	--	--	--
1-20-0930	Drain 5	6L	38.7	185	9.5	2.1	--
-1640	Check	--	12	176	--	--	--
1-21-0930	Drain 6	7L	--	--	9.4	0.99	--
-1630	Check	--	17.7	178	--	--	--
1-22-1030	Drain 7	8L	33.6	179	9.8	1.4	--
-1630	Check	--	4.2	178	--	--	--
1-23-0945	Drain 8	9L	4.9	176	7.8	0.25	--
-1620	Check	--	4.8	178	--	--	--
1-26-1040	Sample	10L	7.1	175	6.6	0.21	--
1-27-1620	Check	--	7.5	178	--	--	--
1-28-1610	Check	--	8.4	178	--	--	--
1-29-0800	"	--	9.2	176	--	--	--
1-30-0825	Sample	5C,6C	10.1	175	--	--	0.029
2-2-0805	--	--	13.2	180	--	--	--
2-3-1020	Drain 9	11L	11.9	183	6.7	11.5	<.003
2-4-1300	Check	--	3.5	165	--	--	--
2-5-0800	"	--	5.3	175	--	--	--
2-6-0800	"	--	6.3	180	--	--	--

TABLE 12 (Continued)

Date-Hr.	Operation	Sample	Micromho/cm	Temp °F	pH	Na	ppm Cl⁻
2-7-0840	"	--	7.0	190	--	--	--
2-9-1045	Drain 10	12L	7.9	175	6.0	0.23	<.003
2-10-0820	Check	--	6.2	175	--	--	--
2-11-0815	"	--	7.8	180	--	--	--
2-12-1530	"	--	8.9	180	--	--	--
2-13-0800	Check	--	9.4	180	--	--	--
-1400	Sample	13L	8.2	180	5.9	<0.23	<.003
2-16-1050	"	14L	9	180	6.0	<0.23	<.003
2-17-0905	Drain 11	--	10.6	182	--	--	--
-0950	Check	--	4.5	160	--	--	--
-1215	"	--	5.4	180	--	--	--
2-18-1345	"	--	7.1	180	--	--	--
2-19-0800	"	--	7.6	185	--	--	--
2-20-1051	"	--	8.6	185	--	--	--
2-21-1019	Sample	15L	9.3	180	6.0	<.1	.064
2-22-0745	Check	--	8.8	180	--	--	--
2-23-1500	Sample	16L	9.7	185	5.9	<.1	.04
2-24-0810	Check	--	9.5	185	--	--	--
2-25-0806	Drain 12	--	10.5	185	--	--	--
2-26-0910	Check	--	5.0	180	--	--	--
2-27-1420	Sample	17L	6.1	180	5.7	<.1	<.01
3-2-1410	Sample	18L	8.4	180	5.6	<.1	<.01
3-3-0800	Check	--	9.0	180	--	--	--
3-4-0830	Check	--	10.6	180	--	--	--
3-5-1000	Drain 13	--	12.0	185	--	--	--
3-6-0813	Check	--	6.1	190	--	--	--
3-9-0813	Sample	19L	10.7	185	5.8	<.23	0.43
3-10-0820	Check	--	10.9	190	--	--	--
3-11-1630	"	--	13	190	--	--	--
3-12-1320	"	--	14.5	185	--	--	--
3-13-0918	Sample	20L	16.2	185	5.7	<.1	<.01
3-16-0745	"	21L	--	--	5.6	<.1	<.01

TABLE 12 (Continued)

Date-Hr.	Operation	Sample	Micromho/cm	Temp °F	pH	Na	ppm Cl^-
3-17-1050	Drain 14	"	22	180	--	--	--
3-18-0955	"	"	10.7	180	--	--	--
3-19-0830	Drain 15	"	12.4	180	--	--	--
3-20-0936	Check	"	8.9	183	--	--	--
3-23-0828	Sample	22L	18.1	185	5.9	<.23	<.01
-0850	Drain 16	--	--	--	--	--	--
-0930	New Pump	--	--	--	--	--	--
-0935	New Pump	--	--	--	--	--	--
3-24-0818	Check	--	7.92	188	--	--	--
3-25-0815	"	--	10.0	185	--	--	--
3-26-0823	Drain 17	--	12.8	182	--	--	--
3-27-1021	Sample	23L	7.3	182	6.0	<.23	<.01
3-30-0830	Drain 18	24L	11.5	185	6.0	<.23	<.01
4-1-0755	Check	--	7.5	187	--	--	--
4-2-1000	"	--	8.3	175	--	--	--
4-3-1550	Sample	27L,25L	10.2	185	6.5	.08	<.01
4-4-1025	Drain 19	28L,26L	11.9	182	6.0	.09	<.01
4-7-1102	Check	--	5.6	180	--	--	--
4-9-1300	Check	--	8.0	183	--	--	--
4-10-1436	Sample	27L	8.9	182	6.0	0.09	<.01
4-13-0846	Drain 20	28L	10.1	182	6.0	0.08	<.01
4-14-0920	Check	--	5.2	186	--	--	--
4-15-0815	"	--	6.2	182	--	--	--
4-16-0803	Drain 21	29L	7.1	180	6.5	0.1	<.01
4-20-1500	Sample	30L	9.7	182	6.0	0.04	<.01
4-21-1320	Check	--	9.3	180	--	--	--
4-22-1318	Drain 22	--	10.2	180	--	--	--
4-23-0804	Check	--	5.2	185	--	--	--
4-24-0806	"	--	6.4	185	--	--	--
4-27-0748	Sample	31L	9.1	185	6.0	0.12	<.01
4-29-0745	Check	--	9.9	190	--	--	--
4-30-0730	Drain 23	--	10.6	180	--	--	--

TABLE 12 (Continued)

Date-Hr.	Operation	Sample	Micromho/cm	Temp °F	pH	Na	ppm Cl^-
5-1-1530	Sample	32L	5.5	180	6.0	0.08	<.01
5-4-0800	Check	--	7.1	180	--	--	--
5-5-0740	"	--	8.1	180	--	--	--
5-6-0807	"	--	9.4	185	--	--	--
5-7-0807	"	--	9.9	180	--	--	--
5-8-0750	Drain 24	33L	10.8	175	6.5	0.04	<.01
5-11-1410	Sample	34L	8.2	195	6.5	0.04	<.01
5-12-0755	Check	--	7.3	188	--	--	--
5-13-0740	"	--	8.0	180	--	--	--
5-14-0740	Check	--	8.7	180	--	--	--
5-15-0740	Sample	35L	9.4	180	6.5	0.04	<.01
5-18-1515	"	36L	9.8	180	6.5	0.04	<.01
5-19-1320	Check	--	9.1	180	--	--	--
5-20-0735	"	--	9.6	180	--	--	--
5-21-0825	Drain 25	--	10.2	180	--	--	--
5-22-0900	Sample	37L	4.4	175	6.5	0.04	<.01
5-26-1540	"	38L	7.6	180	6.5	0.04	<.01
5-27-1018	Check	--	7.7	188	--	--	--
5-28-1111	"	--	8.3	180	--	--	--
5-29-0750	Sample	39L	8.9	180	6.5	0.04	<.01
6-1-1311	"	40L	9.4	180	6.5	0.04	<.01
6-2-1240	Check	--	8.5	180	--	--	--
6-3-0856	"	--	9.3	180	--	--	--
6-4-0745	"	--	10.0	185	--	--	--
6-5-0745	Drain 26	41L	10.1	180	6.5	0.05	<.01
6-8-0730	Sample	42L	6.0	182	6.0		<.01
6-9-0745	Check	--	6.1	185	--	--	--
6-10-0745	"	--	6.6	182	--	--	--
6-11-0830	"	--	7.1	182	--	--	--
6-12-1430	"	--	7.9	180	--	--	--
6-15-0730	Sample	43L	9.5	188	6.0		<.01
6-17-1045	Check	--	9.2	180	--	--	--

TABLE 12 (Continued)

Date-Hr.	Operation	Sample	Micromho/cm	Temp °F	pH	Na	ppm Cl⁻
6-18-1440	"	--	9.6	180	--	--	--
6-19-1440	Drain 27	44L	10.0	180	6.2	0.04	<.01
6-22-0736	Sample	45L	6.8	182	6.5	0.04	<.01
6-23-1335	Check	--	6.9	179	--	--	--
6-24-0750	"	--	7.4	180	--	--	--
6-30-1012	"	--	10.6	180	--	--	--
7-2-0940	Drain 28	46L	11.5	180	6.5	0.04	<.01
7-7-0745	Sample	47L	8.4	182	6.5	0.04	<.01
7-8-1310	Check	--	8.1	182	--	--	--
7-9-0845	Check	--	8.8	182	--	--	--
7-10-0850	Check	--	9.6	180	--	--	--
7-14-0731	Drain 29	48L	14.1	181	6.5	0.04	<.01
7-16-0730	Check	--	7.6	190	--	--	--
7-17-0735	"	--	8.7	188	--	--	--
7-20-0906	"	--	12.1	188	--	--	--
7-21-1038	"	7C,8C	13	188	6.5	<.01	<0.14
-1043	Withdraw model, end of test						

TABLE 13

DIONEX AND FLAMELESS ATOMIC ADSORPTION ANALYSES OF PROOF TEST WATER BATH SAMPLES

	Dionex, ppm		Adsorption, ppb			
Sample(1)	Cl^-	F^-	Fe	Cr	Ni	Na
1C			<1	<1	14	23
2C	0.015	0.232				
3C			83	8	7	33,900
4C	0.365	0.069				
5C			12	4	19	250
6C	0.027	0.054				
7C			10.3	<1	436	5.6
8C	0.144	<.003				

(1) Refer to Table 12 for date of sampling.

TABLE 14

POST TEST PRESSURE MEASUREMENTS ON PROCESS PROOF TEST PRESSURIZED PINS

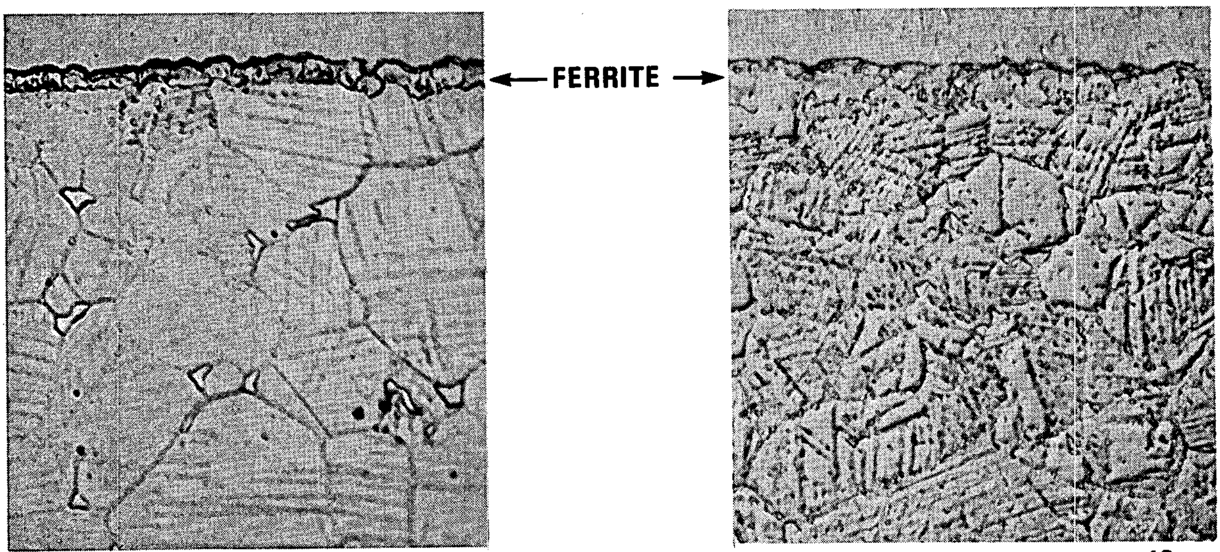
Pin Location No.	Type	Post Test* Pressure, psig (19°C)
19	Interstitial Transfer Facility	Sample Lost
20	Interstitial Transfer Facility	373
21	Interstitial Transfer Facility	366
22	Interstitial Transfer Facility	378
26	From Development Test	418
27	Interstitial Transfer Facility	373
28	Interstitial Transfer Facility	418
32	From Development Test	Sample Lost
33	From Development Test	399
37	From Development Test	373

---

*Pre-test pin pressures nominally 360 psig (19°C).

TABLE 15
POST TEST WEIGHT CHANGE SUMMARY FOR PROCESS PROOF TEST PINS

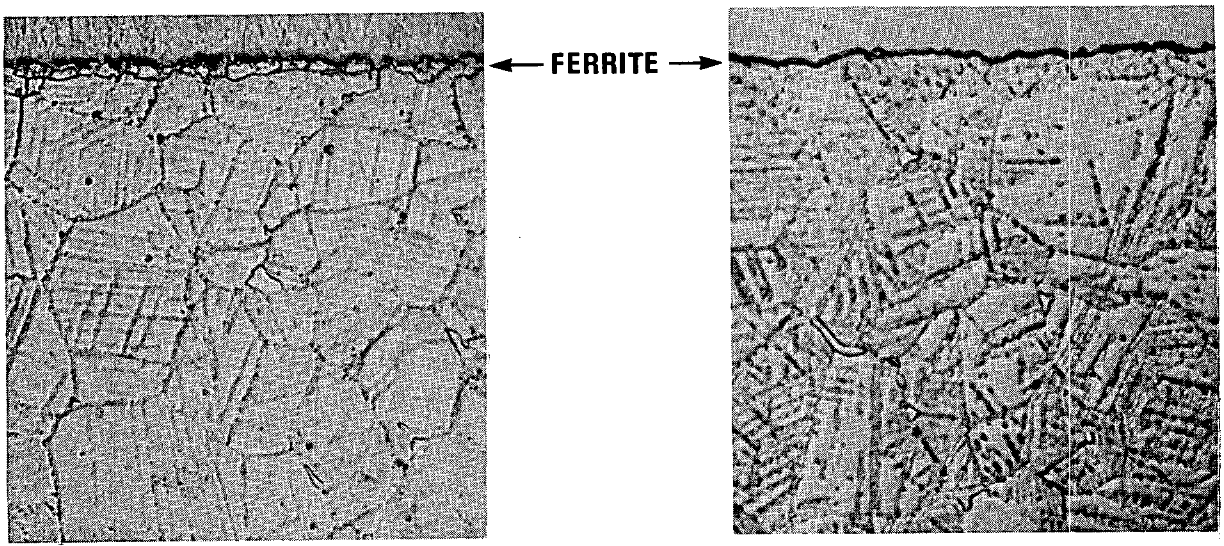
Type (#)	Average ΔW.mg
Interstitial Transfer Facility (6)	-4.6
Development Test (4)	-9.9
AS-FAB (1)	-0-
AS-FAB (8)	-1.8
AS-FAB (18)	+2.4



a) B-17 (LIGHT ETCH) 10μm

c) B-18 10μm

ETCH: 6 GLYCEROL/5 HCl/4HNO$_3$



b) T-17 10μm

d) T-18 10μm

Figure 30. Microstructural Appearance of Cladding Samples Used to Monitor Corrosion Conditions of Model Fuel Pins at 650°C/2000L in ITF Runs #17 and #18. Transverse Sections of the Outside Wall. Showing Ferrite Layer Thickness, are Illustrated for Maximum (B–) and Minimum (T–) Corrosion Locations

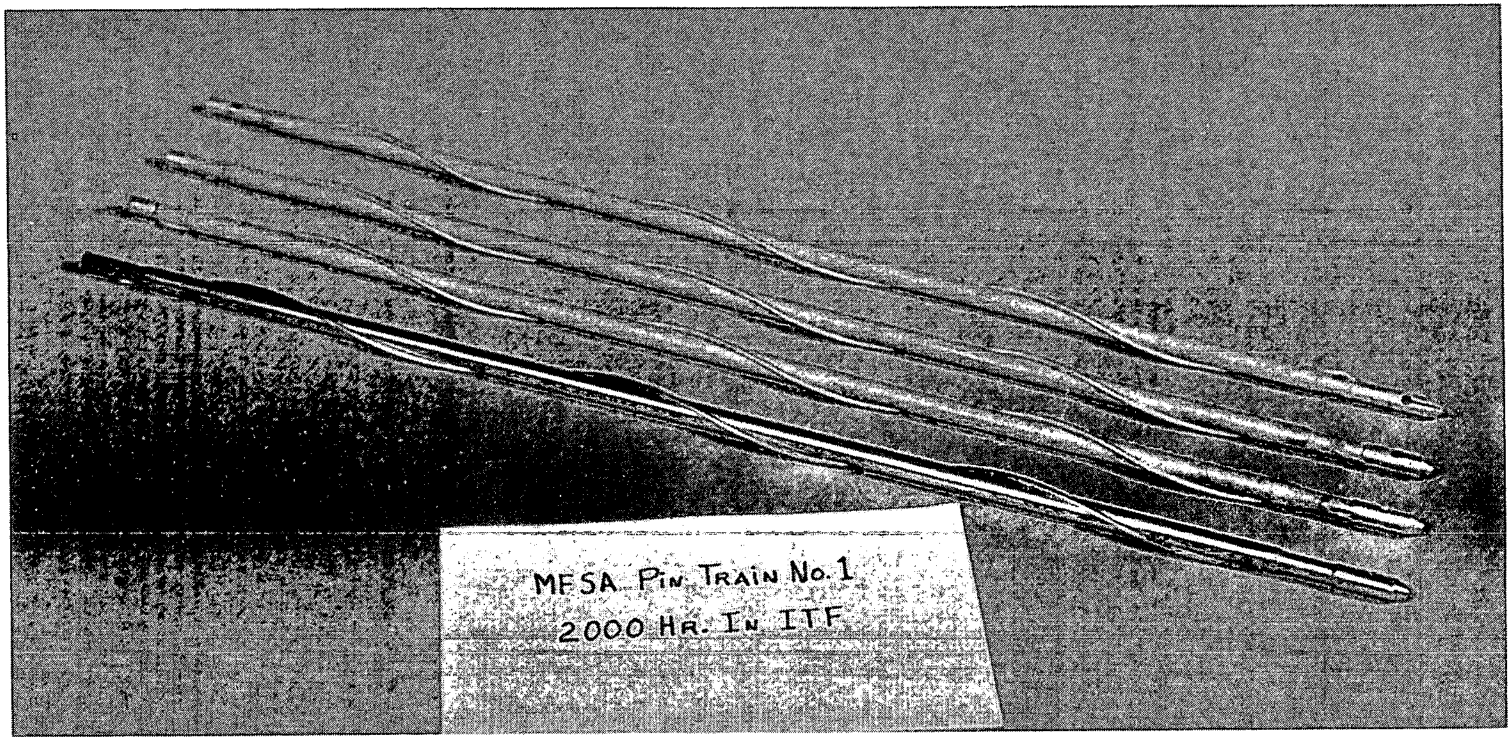


Figure 31. Sodium Corroded Model Pins from ITF Run No. 17

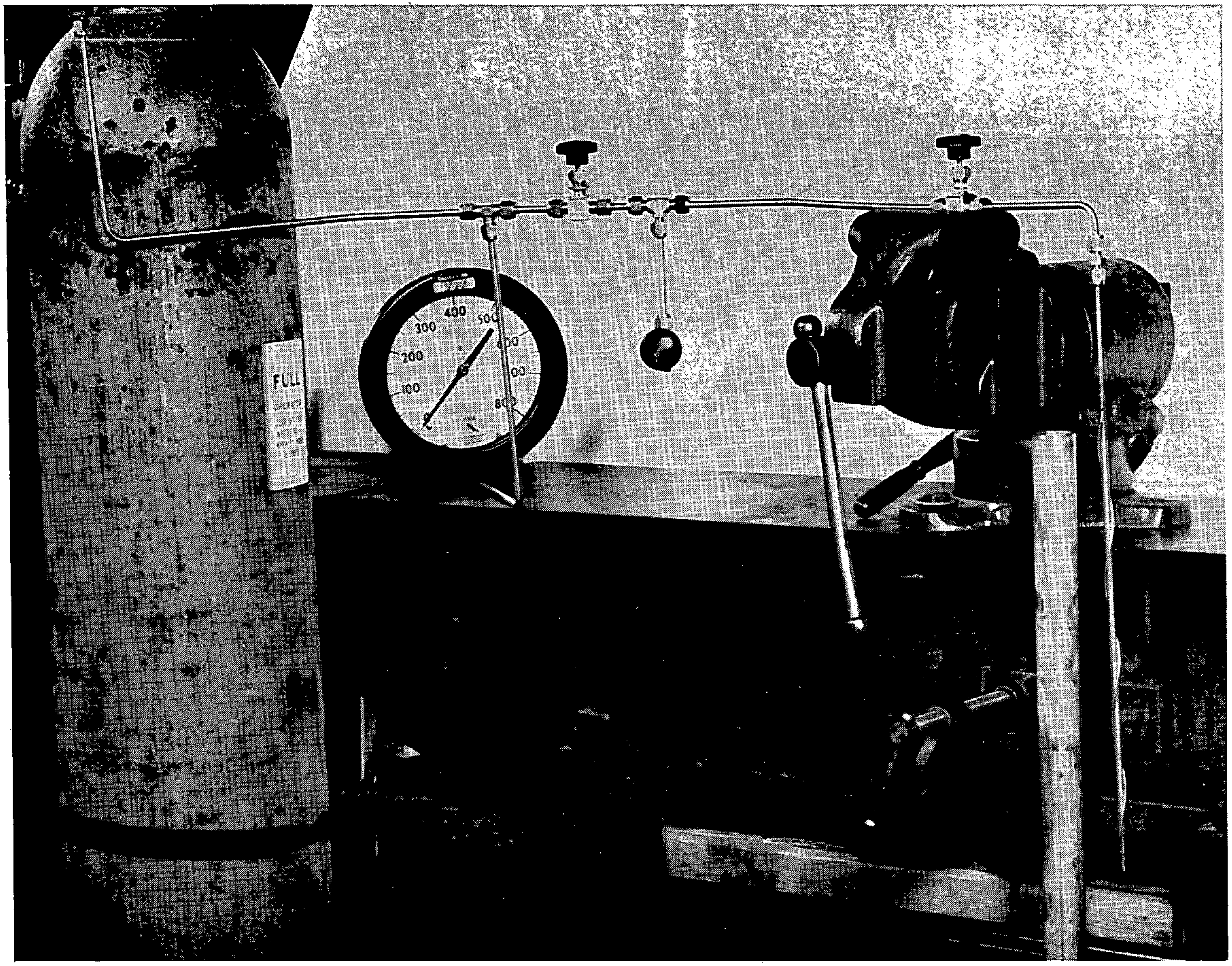


Figure 32. Argon System Used to Pressurize Proof Test Pins

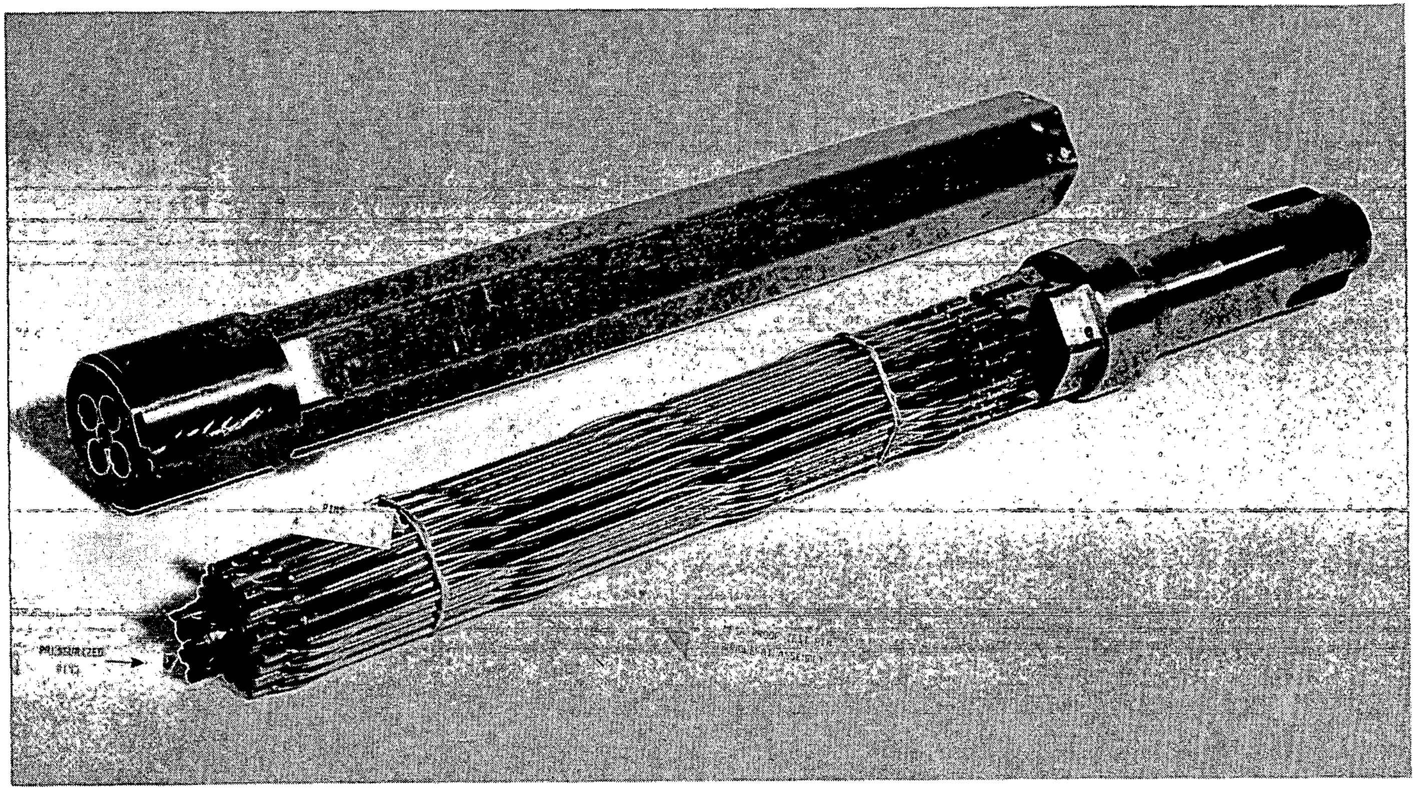


Figure 33. Proof Test Model at Assembly

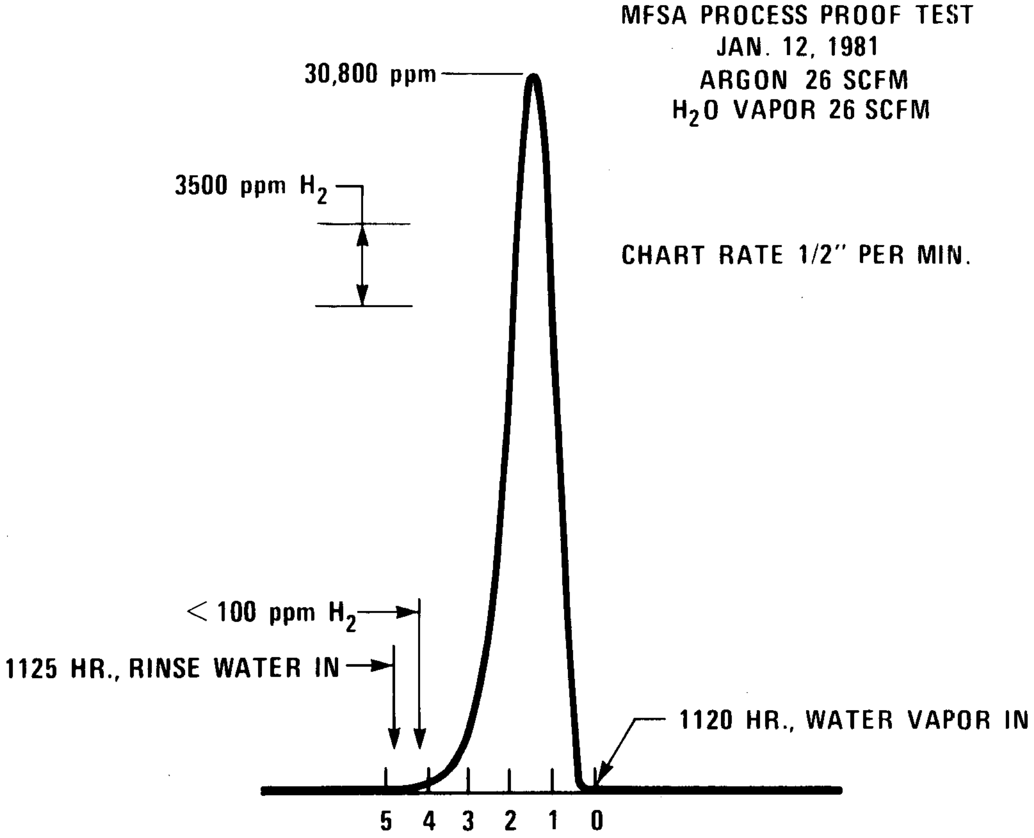


Figure 34. Effluent Hydrogen Concentration Profile for Process Proof Test

6254-15

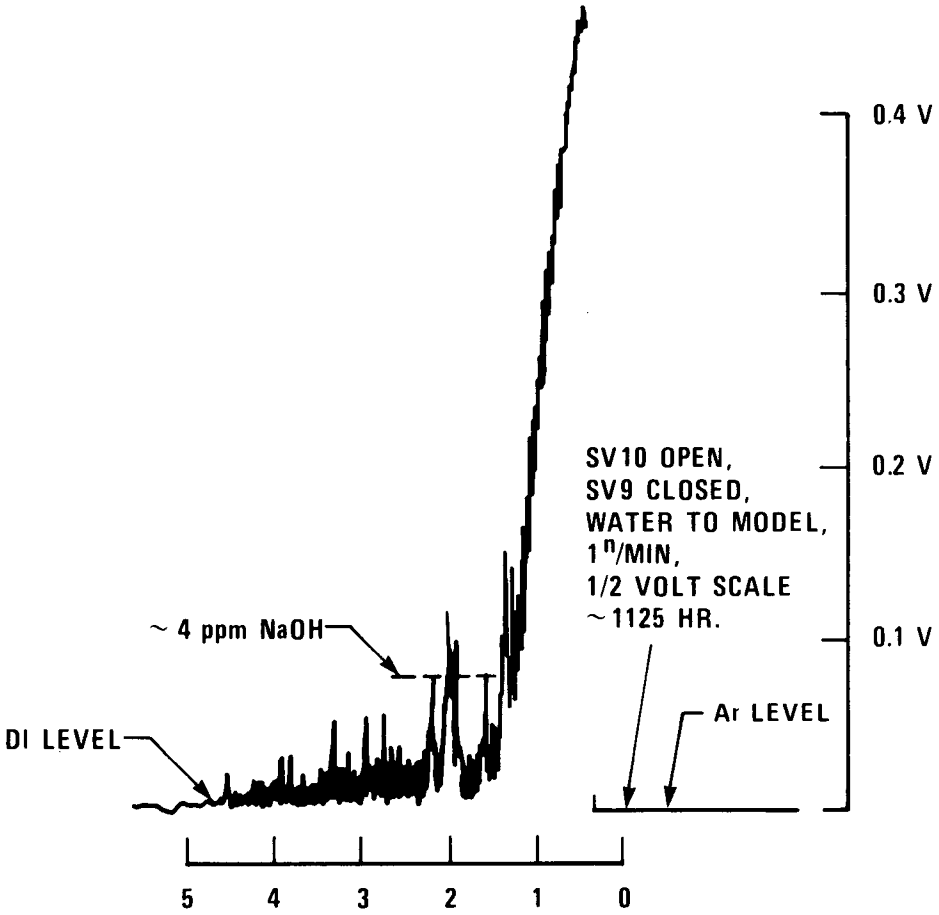


Figure 35. Effluent Resistance Probe Profile for Process Proof Test

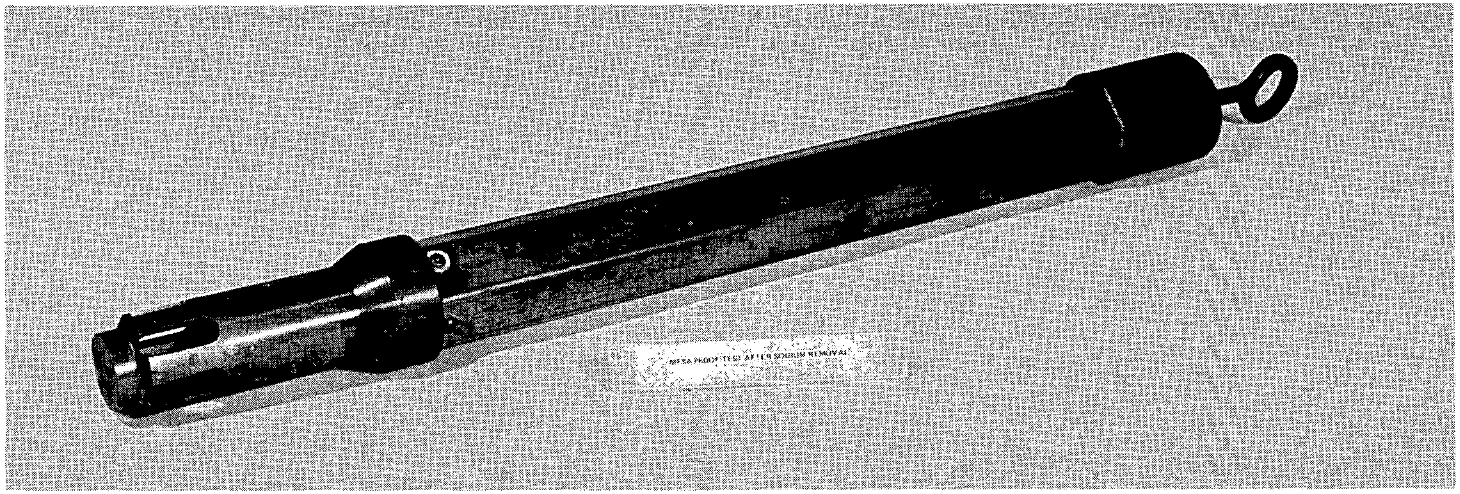


Figure 36. Proof Test Model Following Sodium Removal

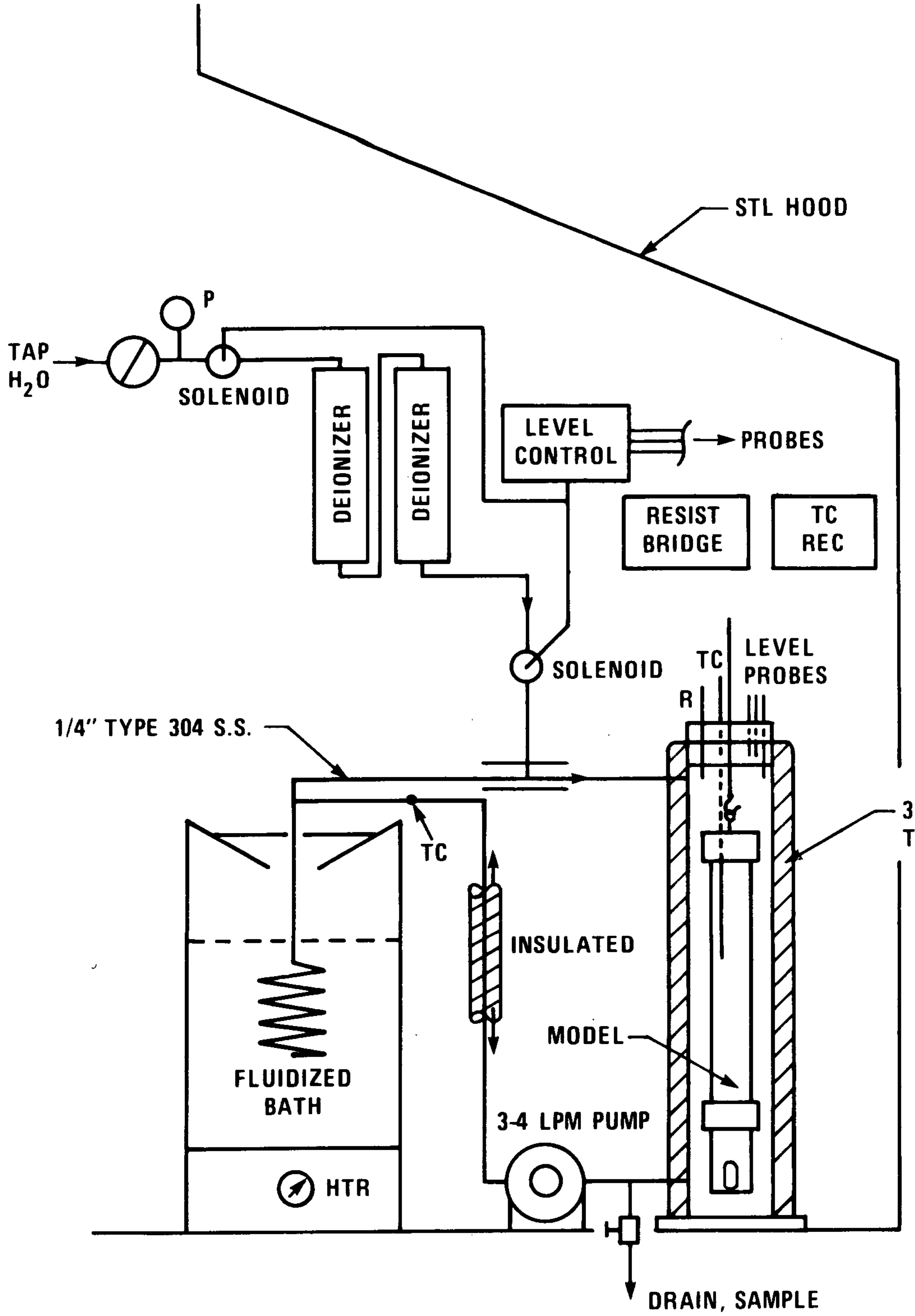


Figure 37. Test Model Water Test Facility

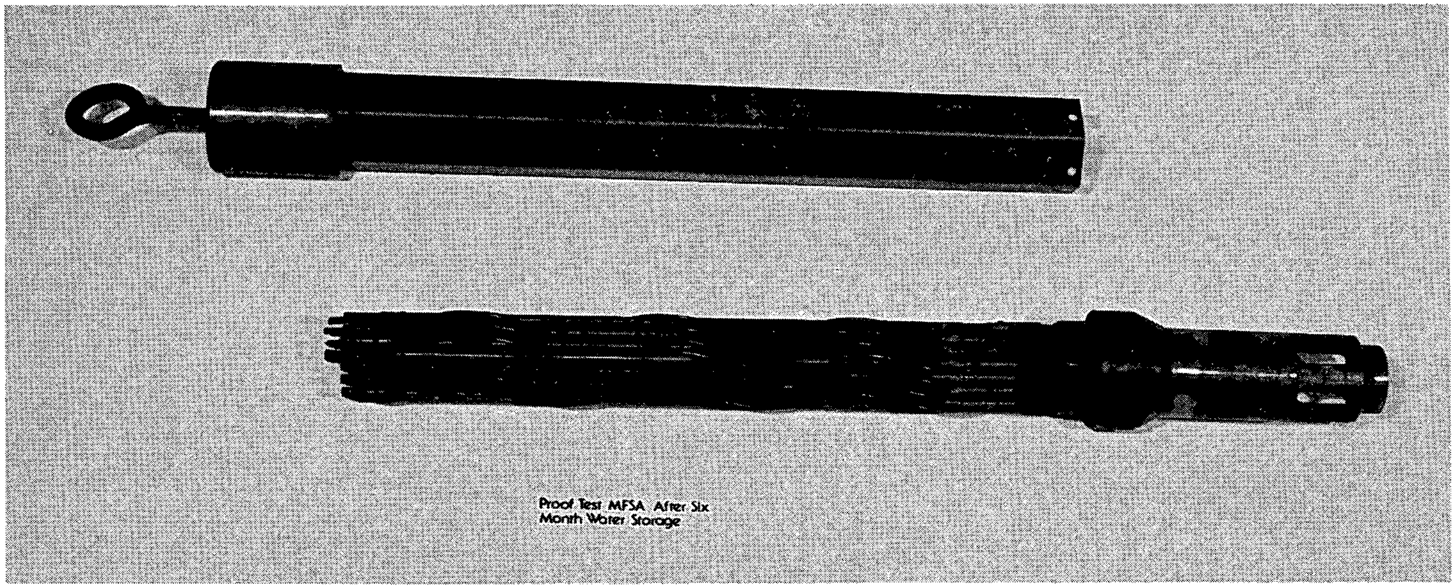


Figure 38. Proof Test Model After Six Month Water Storage

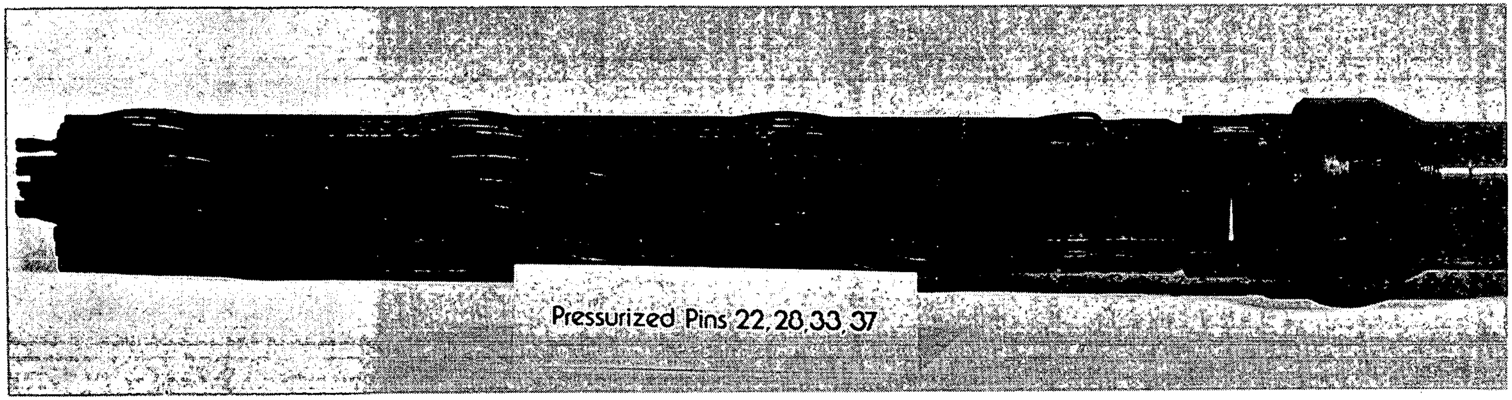
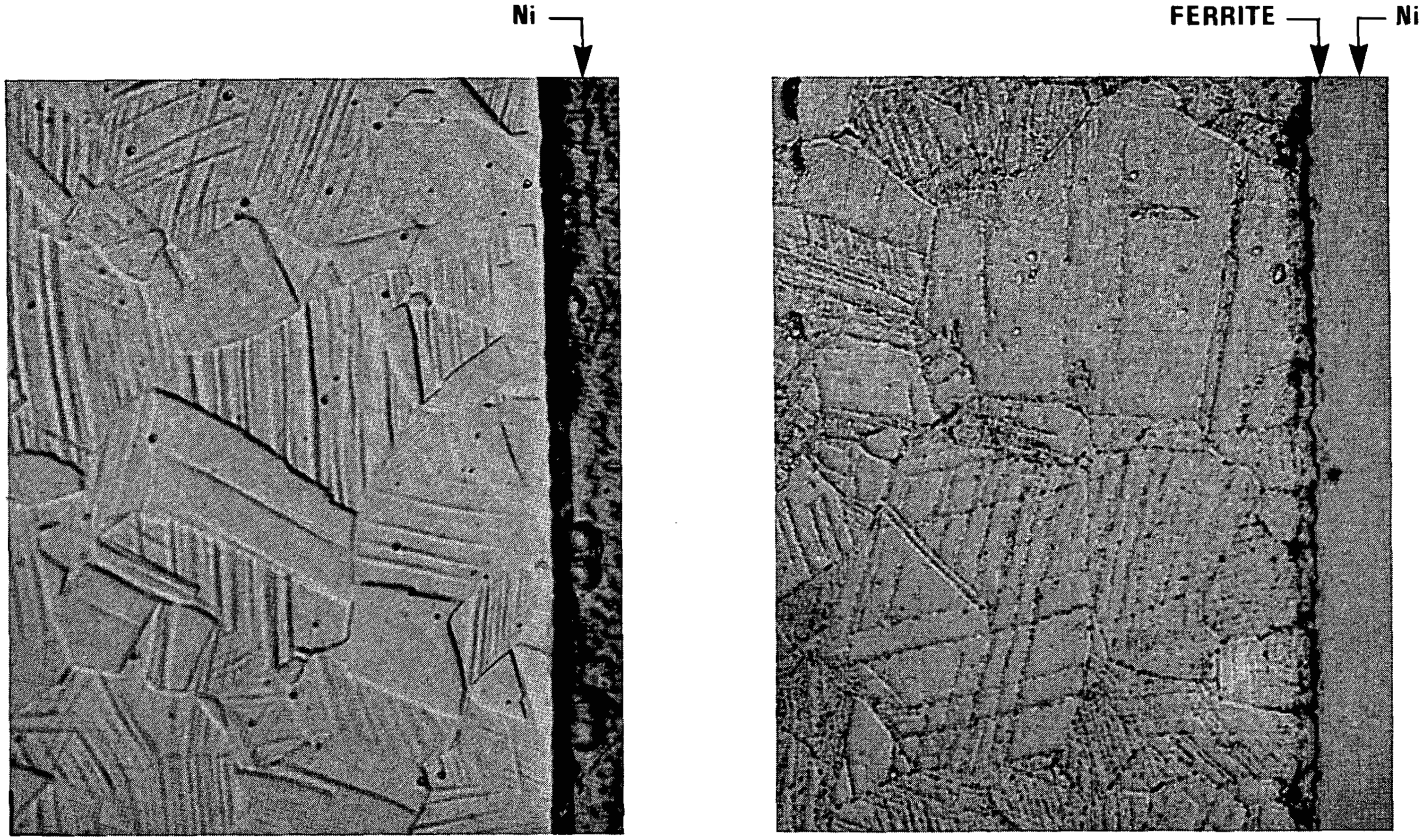


Figure 39. Proof Test Pins Following Water Storage

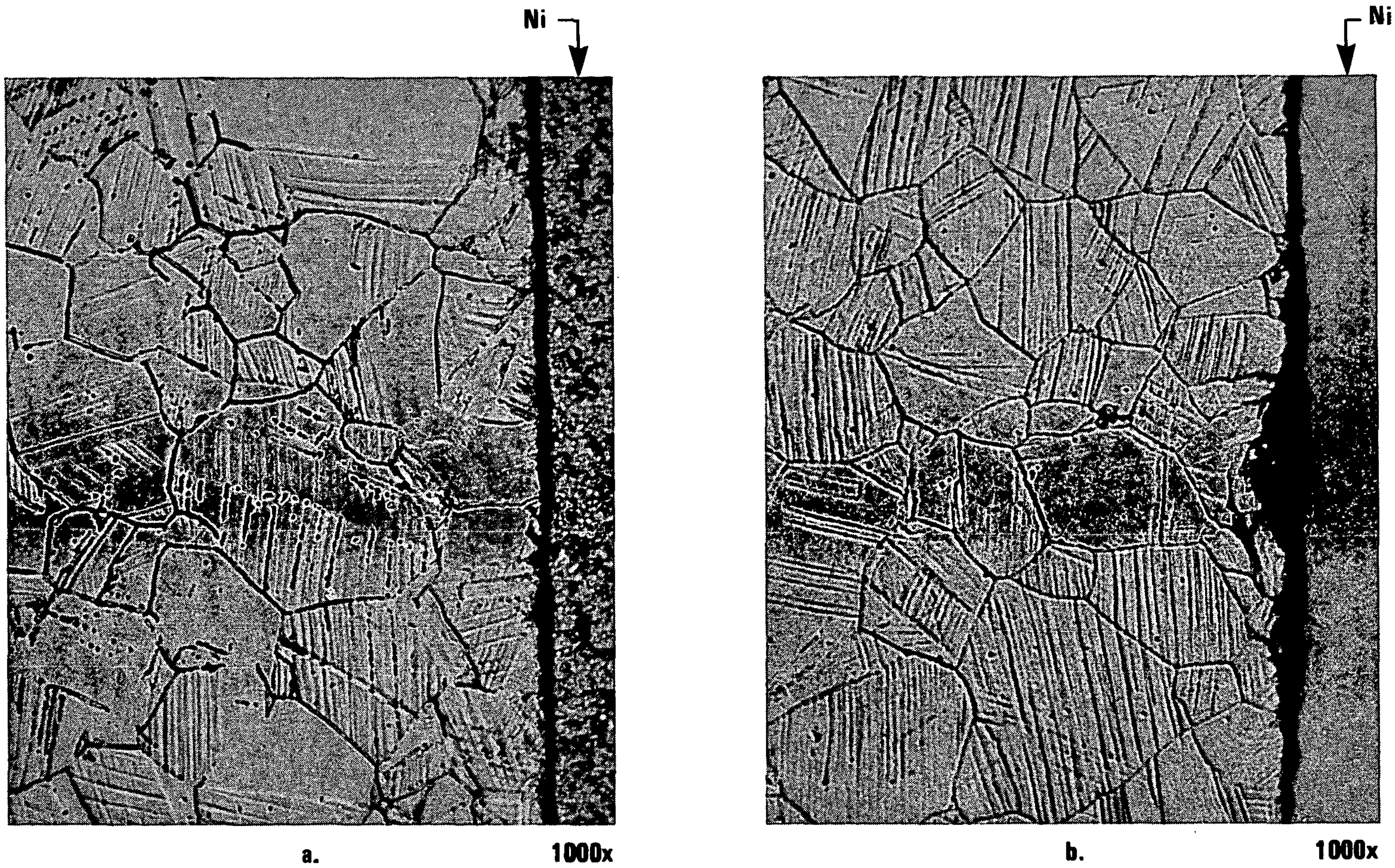


a. 1000x

b. 1000x

Gly/HCL/HNO_3 ETCH

Figure 40. Microstructure of Type 316, 20% Cold Worked Test Model Pin Cladding
a. As-Received, Untested Standard
b. Proof Test Pressurized Pin No. 28 (2000 hrs. in 650°C Sodium, Sodium Removal at 300°F, 4512 hrs. in 82°C Water Bath)



$Gly/HCL/HNO_3$ ETCH

Figure 41. Microstructure of Type 316, 20% Cold Worked Test Model Pin Cladding
a. Proof Test, As-Fabricated Pin No. 16
b. Pressurized Proof Test Pin No. 26 (Six Sodium Wettings, Four Sodium Removals, 4512 hrs. in 82°C Water Bath)

CONCLUSIONS

This section of the report provides the analytical basis for and the extrapolation of model test data to an equivalent Clinch River Breeder Reactor Plant fuel subassembly process and process control for the sodium removal system of the Fuel Receiving Cell, ORNL-HEF.

Analytical Basis for Extrapolations

Assuming bulk sodium concentrations are neglible, film sodium constitutes the major portion of the residual sodium inventory (85% or greater) which will remain on a well-drained fuel subassembly. The model wetting tests described previously for the development tests and the proof test models have substantiated this and indicated an average surface sodium concentration of about 7 mg/cm^2 for the wetted models. This value compares favorably with the 5-10 mg/cm^2 which has been estimated for well-drained, full-scale fuel subassemblies. Analyses in Appendix A.5 indicate that film sodium reaction proceeds essentially as a wave during water vapor injection. Thus, the time required for surface sodium reaction is dependent on the gas velocity, surface sodium concentration and the wetted length involved. For equivalent hydraulic and surface sodium concentration conditions, therefore, the water vapor sodium reaction time in a full-scale subassembly can be estimated from the observed test model sodium reaction data by utilizing the multiplicative length ratio, L CRBR/ L Model. From the data in Table A.2, Appendix A, this length ratio is about 8.2.

The equivalent total gas flow relationship between CRBR (nitrogen) and the test model (argon) based on mass transfer similitudes is given in Appendix A.5 as:

$$F_{CRBR} (SCFM) = 6.95 \times F_{Model} (SCFM)$$

This relationship can be used directly to extrapolate model flow conditions to equivalent hydraulic conditions during water vapor injection to CRBR.

Turning to the water rinse phase of the process, water rinse cleaning time equivalency between CRBR and test model assemblies require equivalent turbulent flow (Reynolds number) and an equivalent number of subassembly volume turnovers. On the basis of the analysis in Section A.5, Appendix A, water rinse flow of equivalent turbulence in the CRBR subassembly is 5.28 times the water flow condition under which the models were tested. Likewise, to obtain an equivalent number of CRBR volume turnovers, the time of water rinse in the CRBR process should be about 15.5 times that in the model tests. It should be noted however, that increasing the water flow rate in the CRBR process above that required by the 5.28 factor will produce the required number of volume turnovers in a shorter rinse time. This latter option should be considered if shorter rinse times are desired and, particularly if recycle of rinse water is planned to minimize the amount of waste water to be treated.

Test Model Data Extrapolation

Utilizing the factors discussed above, the water vapor sodium reaction time, water rinse cleaning time, and equivalent gas and water flows extrapolated from development and proof test data to CRBR process conditions is summarized in Table 16. With the exception of data from Test No. 1, the extrapolated total process time (66-54 minutes) from the model tests all are within the target CRBR time of 30 to 90 minutes per subassembly.

HEF Process Specification

In considering a preliminary specification for the Sodium Removal System of the Fuel Receiving Cell, it is appropriate to evaluate the process proof test results in light of program objectives.

OBJECTIVE:

Permit remote sodium removal processing of spent fuel subassembiles at a rate of 30 to 90 minutes per subassembly.

TABLE 16

MODEL TEST DATA EXTRAPOLATED TO FULL SCALE SUBASSEMBLY SODIUM REMOVAL PROCESS CONDITIONS

	Water Vapor - Nitrogen Phase				Water Rinse Phase	
From Test	Total Flow SCFM	Internal Flow SCFM (1)	v/o H_2O	Phase Time Min.	Total Flow GPM	Phase Time Min.
1	278	208.5	50	67.2	6.9	186 (2)
2	316	237.2	52	44.3	22.7	21.7
3	278	208.5	65	41.0	17.4	23.2
Proof Test	361	270.8	50	34.4	22.7	20.2

---

(1) Calculated on the basis of using the test model orifice plate with a flow division ratio of .75.

(2) Due to the absence of resistance probe data, calculated for the total model rinse time of 12 minutes for this test.

RESULT:

The results given in Table 16 indicate a CRBR total process time extrapolated from the proof test data of about 54 minutes, in the lower end of the target rate range. The flows of inert gas, water vapor and water in the model tests were controlled by solenoid and pneumatic valve operations which could be pre-set to deliver different levels of flow. This concept of flow control is amenable to remote operations. With respect to process end-points, the ability to monitor hydrogen and resistance and/or specific conductance in the effluent inert gas and rinse water respectively were utilized and demonstrated in the model tests. With selection of analytical instrumentation of appropriate sensitivity and remote read-out capability, remote control of full-scale processes in the Sodium Removal System on these two control parameters should be possible.

OBJECTIVE:

Demonstrate that deleterious effects relative to the spent fuel cladding do not occur during the sodium removal process nor during subsequent water storage.

RESULT:

No significant physical or corrosion damage was accrued in sodium-corroded model pins with typically "spent fuel" ferritic surfaces during 300°F sodium removal nor during 4512 hours of storage under 82°C water of typical FRC water pool chemistry.

OBJECTIVE:

Demonstrate compatibility with the SRS and contingent facilities of the HEF and permit sodium removal at a process temperature of 300°F from spent fuel subassemblies generating up to 15 KW decay heat.

RESULTS:

All of the model sodium removal tests were performed successfully at 145° to 155°F (293°-311°F) with no damage to pins or hardware and with almost complete sodium and caustic removal. With respect to compatibility and decay heat cooling, it is appropriate to consider the design concept for the Sodium Removal System generated by Aerojet Manufacturing Company.(1) Conceptual decay heat cooling, sodium removal processing times and waste rinse water requirements under this concept are compared with similar CRBR parameters extrapolated from the process proof test in Table 17. From this comparison, almost equivalent nitrogen hydraulic compatibility is indicated. Important to equipment availability schedules and the target process load of HEF (0.5 metric ton per day), the extrapolated total process time is about 15 minutes less than the Aerojet concept. The waste rinse effluent requirement of 50 gallons per subassembly obviously requires recycle of water under the extrapolated flow rate to produce the required system volume turnovers. On the basis of extrapolated water flow, flow time and the CRBR volume parameter given in Section A.5, Appendix A, the required CRBR system volume turnovers from the model rinse data is about 126. Finally, the model test data for residual sodium indicate that minimal amount of sodium or caustic will be transferred on subassemblies to the water pool of the HEF. The level of pool contamination per subassembly should be small and could be easily removed, for example, by an appropriate ion exchange purification circuit for the pool.

In summary then, the recommended preliminary process specification for HEF is embodied in the extrapolated flow and water vapor content parameters given in Table 17 from the process proof test. Process control of the water vapor and water rinse phases are recommended to be by effluent hydrogen concentration decay to a predetermined low level (100-300ppm) and by leveling of specific conductance (resistance) respectively. The leveling requirement is necessary since recycling of water is assumed to occur in the plant Sodium Removal System.

TABLE 17
HEF CONCEPTUAL PROCESS COMPARED WITH EXTRAPOLATED PROOF TEST PARAMETERS
FROM SODIUM REMOVAL SYSTEM CONCEPTUAL DESIGN
(AMCO 1974-78-(02)-ER)

- For 300°F, latm. cooling at sodium removal (0.8 orifice)
  - N_2 Carrier flow, Total ∿270 cfm ∿175 SCFM
  - N_2 Carrier flow, Internal ∿140 SCFM
- 50 gallons of waste rinse recycle effluent per subassembly
- Total estimated cleaning time ∿69.5 minutes per subassembly

FROM PROCESS PROOF TEST (0.75 ORIFICE)

- Water vapor phase (50 v/o water vapor)
  - N_2/H_2O flow, Total ∿361 SCFM
  - N_2 flow, Total ∿181 SCFM
  - N_2 flow, Internal ∿136 SCFM
  - WVN Process Time ∿34 minutes
- Water Rinse Phase
  - H_2O flow, Total ∿23 GPM
  - Rinse Time ∿20 minutes
- Total Cleaning Time ∿54 minutes per subassembly

RECOMMENDATIONS

This section is devoted to recommendation of additional programs utilizing the current W-ARD Fast Sodium Removal Facility. Three additional programs believed to be of sufficient current interest to warrant extension of the present program scope are recommended and described.

A. Extension of Test Scope to Include Ferritic Materials. Current large LMFBR design concepts consider the incorporation of ferritic alloys for cost effectiveness and because of general austenitic alloy availability problems. The use of ferritic alloys in fuel subassemblies has certain advantages such as amelioration of the swelling problem associated with current austenitic clads. With respect to sodium removal, the principal concern with the use of ferritic claddings would be hydrogen embrittlement. It is proposed that rapid sodium removal tests utilizing the existing model design with ferritic material incorporated can be easily performed in the existing test facilities at nominal additional time and cost. The principal cost and time involvement would be in the procurement and fabrication of ferritic components for the test model.

B. Investigate the Feasibility of Eliminating the Initial Phase of the Sodium Removal Cycle. The absence of thermal transients, production of manageable amounts of hydrogen and the absence of catastrophic physical and corrosion damage in the current high temperature model tests intimate that the feasibility of eliminating the water vapor injection phase should be investigated. For this purpose, tests are proposed, using the current test model, in which the sodium-wetted model (heated in argon) would be injected with deionized water directly. The current test facility could be utilized, the only modification being the incorporation of a hydrogen disengagement vessel on the system effluent line to permit H_2 monitoring throughout the process.

C. Sodium Removal Demonstration at Full Scale Using an Available Flow Subassembly. Extrapolation of the current model test data are based on hydraulic and mass transfer-based factors determined by idealized analyses. It is proposed to verify the extrapolated process parameters recommended for the Sodium Removal System by performing a rapid sodium removal on a full-sized flow test fuel subassembly currently available at W-ARD. With some modifications of the pin bundle and end hardware flow channels to produce typical sodium retainment features, this subassembly could be sodium-wetted in the large sodium loop (General Purpose Loop-2) at W-ARD and sodium removal performed using the existing automated fast sodium removal systems. Principal modifications to the system would be the fabrication of a suitably-sized orificed cleaning vessel and up-grading the steam supply system controls (valves, turbine meter) and argon supply system rotameter (recalibration) to the higher required flow rates. The time and cost of this proposed project would, principally, be commensurate with modification efforts and the cost of GPL-2 sodium wetting.

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APPENDIX A

DESIGN CONSIDERATIONS FOR A FUEL SUBASSEMBLY RAPID SODIUM REMOVAL SYSTEM

A.0 SUPPORTING DATA: DESIGN CONSIDERATIONS FOR A FUEL SUBASSEMBLY RAPID SODIUM REMOVAL SYSTEM

In the following sections, the heat and mass transfer relations are analyzed in detail for a CRBR fuel subassembly and the proposed scale test model, considering the use of either nitrogen or argon carrier gas. From these analyses, the minor differences are illustrated and the equivalent conditions for a fast sodium removal process on a CRBR fuel subassembly using nitrogen, and the sodium removal process on the test model using argon are discussed.

In Section A.1, the heat and mass transfer coefficients in the two systems are evaluated. In Section A.2, these data are used to evaluate the gas flow required to assure acceptably low fuel cladding surface temperatures in a subassembly generating 15 kw decay heat. In Section A.3, the additional heat removal requirements due to the sodium/water reaction are discussed. In Section A.4, minimum times required to react the sodium film on the subassembly surfaces are calculated based on the mass transfer data. In Section A.5, equivalent full scale and test model sodium removal processes are discussed.

A.1 HEAT AND MASS TRANSFER COEFFICIENT EQUATIONS

The heat and mass transfer coefficients are calculated from:

1. $\text{Nu (heat)} = 0.023\ \text{Re}^{0.8}\ \text{Pr}^{1/3}\ (\mu_b/\mu_w)^{0.14}$
2. $\text{Nu (mass)} = 0.023\ \text{Re}^{0.8}\ \text{Sc}^{1/3}$

where:

Nu (heat) = hD_e/k, dimensionless
Nu (mass) = $k_x D_e/LD$, dimensionless
Re = $D_e u\rho/\mu$, dimensionless
Pr = $c\mu/k$, dimensionless
Sc = $\mu/\rho D$, dimensionless
ρ = density, g/cm^3
u = linear velocity

D_e = equivalent diameter (4 x flow area/wetted perimeter), cm
μ = viscosity, g/cm.s
c = heat capacity, watt.s./g°C
k = thermal conductivity, watt/cm°C
D = diffusion coefficient, cm^2/s
h = heat transfer coefficient, $watt/cm^2 {}^\circ C$
k_x = mass transfer coefficient, g mole/cm^2.s mole fraction
L = total molar concentration, g moles/cm^3

Using the data in Table A-1, and Equations 1 and 2, the average heat and mass transfer coefficients for argon and nitrogen from 50 to 150°C are:

Argon:

$$h = 3.036\ E\text{-}3\ G^{0.8}\ D_e^{-0.2}$$

$$k_x = 1.679\ E\text{-}4\ G^{0.8}\ D_e^{-0.2}$$

Nitrogen:

$$h = 5.52\ E\text{-}3\ G^{0.8}\ D_e^{-0.2}$$

$$k_x = 2.14\ E\text{-}4\ G^{0.8}\ D_e^{-0.2}$$

with G = mass flow rate, grams/cm^2.s and D_e in cm.

A.2 DECAY HEAT REMOVAL

Calculate the gas mass flow rate required to maintain the fuel pin surface temperature below a fixed temperature--say 121°C (250°F).

Let:

a = wetted surface area per unit length, cm
A = cross-sectional flow area, cm^2
G = gas mass flow rate, g/cm^2.s.
L = fuel pin length, cm
c = heat capacity of gas, watts/g°C

TABLE A-1
GAS PROPERTIES AT ONE ATMOSPHERE

	Temp °C	Density g/cm^3	Viscosity g/cm.s	Heat Capcity watts/g°C	Thermal Conductivity watt/cm°C	Diffusion Coefficient cm^2/sec
Argon						
	50	1.509E-3	2.38E-4	0.521	1.87E-4	0.296
	100	1.307E-3	2.70E-4	0.521	2.10E-4	0.381
	150	1.152E-3	2.91E-4	0.521	2.32E-4	0.474
Nitrogen						
	50	1.057E-3	1.85E-4	1.047	2.74E-4	0.303
	100	0.915E-3	2.21E-4	1.047	3.09E-4	0.390
	150	0.807E-3	2.30E-4	1.047	3.41E-4	0.486

		Pr	Sc	$\frac{k\ Pr^{1/3}}{\mu^{0.8}}$	$\frac{\rho\ DSc^{1/3}}{M\mu^{0.8}}$
Argon					
	50	0.663	0.533	0.1291	7.17E-3
	100	0.670	0.542	0.1316	7.27E-3
	150	0.653	0.533	0.1357	7.46E-3
				0.132 ave	7.30E-3 ave
Nitrogen					
	50	0.707	0.578	0.236	9.23E-3
	100	0.749	0.619	0.236	9.12E-3
	150	0.706	0.586	0.247	9.54E-3
				0.240 ave	9.30E-3 ave

P = decay heat, watts
T_s = fuel pin surface temperature, °C, at x cm from inlet
T_g = gas temperature, °C, at x cm from inlet
h = heat transfer coefficient, watt/cm^2°F

Neglect axial flow of heat in the fuel pin, i.e., heat flows radially out only.

Assume decay heat flux is a function of x, the distance along the fuel assembly, f(x) watt/cm

Then:

1. $P = \int_0^L f(x)dx$

Heat balance over differential length:

2. $GAc\ dT_g/dx = f(x)$
3. $f(x) = ha\ (T_s - T_g)$

From Equation 2,

4. $T_g - T_{gi} = \int_0^x f(y)dy/GAc$

Substituting Equation 4 in Equation 3 and solving for Ts,

5. $T_s = T_{gi} + \int_0^x f(y)dy/GAc + f(x)/ha$
T_{gi} = Gas inlet temperature

Assume f(x) is a chopped cosine distribution about the core (fuel) center, i.e.,

$f(x) = B \cos \pi\ z/(L+b)$
$z = x - L/2$
$P = \int_0^L f(x)dx = B \int_{-L/2}^{+L/2} \cos \pi\ z/(L+b)\ dz$
$P = \frac{2B(L+B)}{\pi} \sin \pi\ L/2\ (L+b)$
$B = P\alpha/sm\alpha L;\ \alpha = \pi/2\ (L+b)$

6. $f(x) = P(\alpha/\sin\alpha l) \cos 2\alpha Z$

and

$$_{0}\int^{x} f(y)dy = {}_{-L/2}\int^{z} P(\alpha/\sin\alpha L) \cos 2\alpha z \, dz$$

7. $$= (P/2 \sin\alpha L) (\sin 2\alpha z + \sin \alpha L)$$

Thus, from Equations 5, 6, and 7

8. $$T_s = T_{gi} + (P/2\ GAc \sin\alpha L) (\sin 2\alpha z + \sin\alpha L) + (P\alpha/ha \sin\alpha L) \cos 2\ \alpha z)$$

To find the maximum T_s, equate the derivative of Equation 8 to zero

$$0 = (P/2GAc \sin\alpha L) (2\alpha \cos 2\alpha z) - (2P\alpha^2/ha \sin\alpha L) \sin 2\alpha z$$

from which,

$$\tan 2\alpha z = ha/2GAc\alpha \text{ at } T_s = \max$$

Therefore,

$$T_{s\ max} = T_{gi} + E (\sin \tan^{-1} \beta + \sin\alpha L) + F \cos \tan^{-1} \beta$$

or

$$T_{s\ max} = T_{gi} + E (\sin \tan^{-1} \beta + \sin\alpha L + \cos \tan^{-1} \beta/\beta)$$

where:

$E = P/2GAc \sin\alpha L$

$F = P\alpha/ha \sin \alpha L$

$B = ha/2GAc\alpha = E/F$

$\alpha = \pi/2\ (L+b)$

In Table A-2, the values of the necessary parameters are given for CRBR, PLBR and two potential test fuel subassemblies. From these data the maximum fuel pin surface temperature and overall gas temperature rise, ΔT_g, as a function of G are calculated as shown in Table A-3.

TABLE A-2
HEAT TRANSFER PARAMETER VALUES

	Fuel Assembly Type			
			Test Assembly	
Parameter	CRBR	PLBR	CRBR Type	PLBR Type
P, watts	15,000	15,000		
A, cm^2	47.0	69.3	5.60	10.88
a, cm	436.	723.	82.6	111.5
c, watts/g°C;				
Argon	0.521	0.521	0.521	0.521
Nitrogen	1.047	1.047	1.047	1.047
L, cm (fuel only)	91.4	122.	--	--
(total)	292.	330.	35.5	--
h, watt/cm^2 °C				
De, cm	0.431	0.384	0.271	0.390
b, cm	32.3	35.7	--	--
α, cm^{-1}	12.7E-3	9.96E-3	--	--
h, watt/cm^2 °C (N_2)	6.53E-3$G^{0.8}$	6.68E-3$G^{0.8}$	7.17E-3$G^{0.8}$	6.66E-3$G^{0.8}$
$\sin \alpha L$	0.9171	0.9348		
Number of Pins	217	271	37	37
Pin Diameter, cm	0.584	0.787	0.584	0.787
Wire Wrap Diameter, cm	0.142	0.117	0.142	0.117
Pin Pitch, cm	0.731	0.911	0.731	0.911
Duct Inside Diameter, cm	11.02	15.24	4.23	5.78

TABLE A-3

MAXIMUM FUEL PIN SURFACE TEMPERATURE AND OVERALL GAS TEMPERATURE RISE AS FUNCTION OF GAS FLOW RATE

	Ts_{max}				ΔTg			
	CRBR		PLBR		CRBR		PLBR	
G	N_2	Ar	N_2	Ar	N_2	Ar	N_2	Ar
2	189.2	356.7	130.1	240.2	152.4	306.3	103.4	207.7
4	106.1	190.8	75.6	130.9	76.2	153.1	51.7	103.9
6	78.1	135.1	57.3	94.3	50.8	102.0	34.5	69.2
8	64.0	107.0	48.1	76.0	38.1	76.5	25.8	51.9

A graph of these data shows that to maintain $T_{s\ max}$ at 121°C (250°F) a nitrogen flow of about 3.5 g/cm^{2}s. (2.58 E4 lb/ft^2.hr), or a total flow of 279 scfm in the CRBR fuel subassembly is required. If argon were used, 6.8 g/cm^{2}s or 378 scfm would be required. Likewise, to maintain a CRBR fuel subassembly at 149°C (300°F) a nitrogen flow of about 2.9 g/cm^{2}s. or a total flow of about 220 scfm is required.

A.3 HEAT GENERATION DUE TO SODIUM/WATER REACTION

The reaction of sodium with water generates about 45,000 cal/g mol sodium reacted. It is estimated that the CRBR fuel subassembly will have about 600 g of sodium as a film on the surface after draining. Therefore, the energy released by reaction of this sodium will be 1.174 x 10^6 cal or 4.9 megawatt seconds. If this reaction occurs at a uniform rate over a 30 minute period, the heat generation rate would be 2.73 kw, or 18% of the decay heat value of 15 kw.

Another way of examining this is as follows:

In the following section, it is shown that the mass transfer controlled (upper limit) reaction rate of film sodium at the fuel subassembly surfaces of a CRBR type fuel subassembly is given by:

$$R\ (\text{gNa/cm}^2\text{.s.}) = 0.01587\ C$$

with C = volume fraction water in the carrier gas.

Since the water sodium reaction

$$Na + H_2O = NaOH + 0.5\ H_2$$

generates about 45,000 cal/g mol sodium reacted, the rate of heat generation at the above reaction rate is

$$Q = (45{,}000/23)\ (0.01587\ C)$$

$= 31.1C\ cal/cm^2.s.$

$= 130.0C\ watt/cm^2$

This is a quite significant power, however, it occurs for only a short time, and the heat capacity of the fuel pin plus the transfer of heat to the gas will tend to minimize the temperature rise. For example, the heat transfer coefficient is 17.8×10^{-3} watt/cm^2°C, hence this power could be dissipated by a ΔT of 73°C at a water concentration of 0.01 volume fraction. Thus, the transient overtemperature should be small and of limited duration.

A.4 MASS TRANSFER/CHEMICAL KINETICS CONSIDERATIONS

The mass transfer coefficient using nitrogen carrier gas was shown in Section A.1 to be

$$k_x = 2.14\ E\text{-}4\ G^{0.8}\ D_e^{-0.2}$$

For CRBR type fuel subassembly using $G = 3.5$ g/cm^2.s., $k_x = 6.90 \times 10^{-4}$ g moles/cm^2.s. mole fraction. An upper limit to the rate of sodium reaction is therefore

$$R(gNa\ reacted/cm^2.s.) = (69 \times 10^{-4})\ (23)\ (C) = 0.01587\ C$$

where C is the volume fraction (= mole fraction) water vapor in the carrier gas.

Typical sodium surface film concentrations on drained components are 5 to 10 mg/cm^2. The time required to react a 10 mg/cm^2 film at the above reaction rate would be

$$t(reaction) = 0.01/0.01587C$$
$$= 0.630/C\ seconds$$

or 63 seconds at 1% H_2O concentration. The actual reaction rate would be somewhat lower, since as the sodium reacts, it gradually forms a concentrated sodium hydroxide solution on the surface which hinders mass transfer to the unreacted sodium. Nevertheless, it is expected that the film sodium will react quite quickly in the sodium removal operation, particularly since most of the surfaces are vertical, and hence the solutions will continually drain.

A.5 SCALE DOWN TO TEST FUEL ASSEMBLY

The program plan proposes using a scaled down model of the CRBR type fuel subassembly with characteristics as shown in Table A-2. In addition, the carrier gas will be argon rather than nitrogen. Since there will be no decay heat in the test model, we shall emphasize mass transfer similitude (sodium reaction rate) rather than heat transfer. That is, the mass transfer coefficients have been shown to be

$$k_x\ (N_2) = 2.14\ E\text{-}4\ G^{0.8}\ D_e^{-0.2}$$

$$k_x\ (A_r) = 1.679\ E\text{-}4\ G^{0.8}\ D_e^{-0.2}$$

Thus, for equal mass transfer coefficient, using these expressions for k_x and the D_e's for the model and CRBR fuel subassembly, the required gas flows are related by:

$$G(\text{model}) = 1.206\ G\ (\text{CRBR})$$

and the total gas flows are related by

$$G_T\ (\text{model}) = 0.1437\ G_T\ (\text{CRBR})$$

Since the nitrogen flow requirements in the CRBR fuel subassembly have been shown to be 279 scfm, the argon flow in the test model must be 40 scfm. If heat transfer coefficients were made equal, a similar analysis indicates that the model gas flow would have to be 62 scfm, which would result in 42% increase in mass transfer rate. The desirability of examining the effect of flow will be considered after some experimental results are obtained.

From the rapid sodium reaction rates calculated in the preceeding section it can be shown that the film sodium reaction proceeds essentially as a wave starting at the inlet and proceeding to the outlet. Hence, the time required to react the film sodium will be approximately proportional to the length of the assembly. Thus, if we assume that the ultimate sodium removal scheme will involve a rapid increase in water content in the gas to remove local bulk deposits and some crevice sodium after the surface film of sodium has been reacted, the initial period of flushing with low (e.g., 4%) water vapor content in the gas will be much shorter with the model than with the CRBR assembly (∿1 minute versus 8 minutes). The duration of the high water vapor concentration (e.g., 50%) flush will be comparable in the two cases since the water depletion per pass will be small in this period due to the relatively small surface areas of sodium (crevices and small areas where excess sodium may have hung up) available for reaction, and the reaction time will be dependent on depth of crevices or sodium hang up.

The full liquid water flush period in the test model should be shorter than in the CRBR subassembly if one chooses a system volume criterion. That is, the liquid volume in the test model is 0.168 liters whereas it is 13.72 liters in the CRBR subassembly, and for equal Reynolds number (and hence, turbulence or flushing ability) the required total water flow rates would be in the ratio 5.28 for CRBR/test model. To pass the same number of system volumes through each assembly would take 15.5 (=13.72/0.168 x 5.28) times as long for the CRBR as for the test model. This process water feed schedule for "equivalent" sodium removal in CRBR and test model subassenblies is shown schematically in Figure A-1. It can be seen from the figure that if a sixty-minute process time is desired for the full scale assembly, considerably shorter process times must be proven acceptable in the short 37 pin model.

It must be emphasized that the above analysis is highly idealized. Preliminary analyses of the sodium removal rate data from the previous small scale program on corrosion of fuel pins in water storage after sodium removal indicate that the actual sodium reaction rate is significantly lower than the maximum mass transfer rates calculated as above. This can be compensated for by increasing the initial water vapor content in the feed, increased gas flow rates, and increased temperature within acceptable limits.

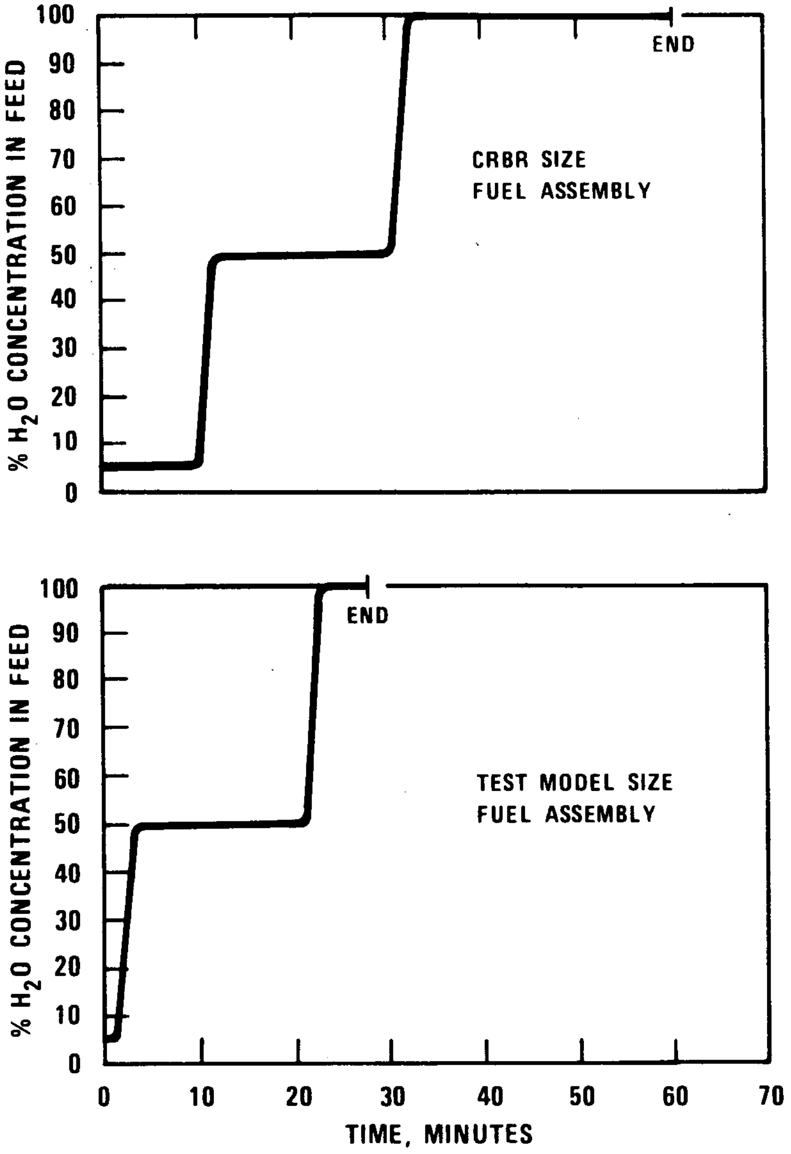
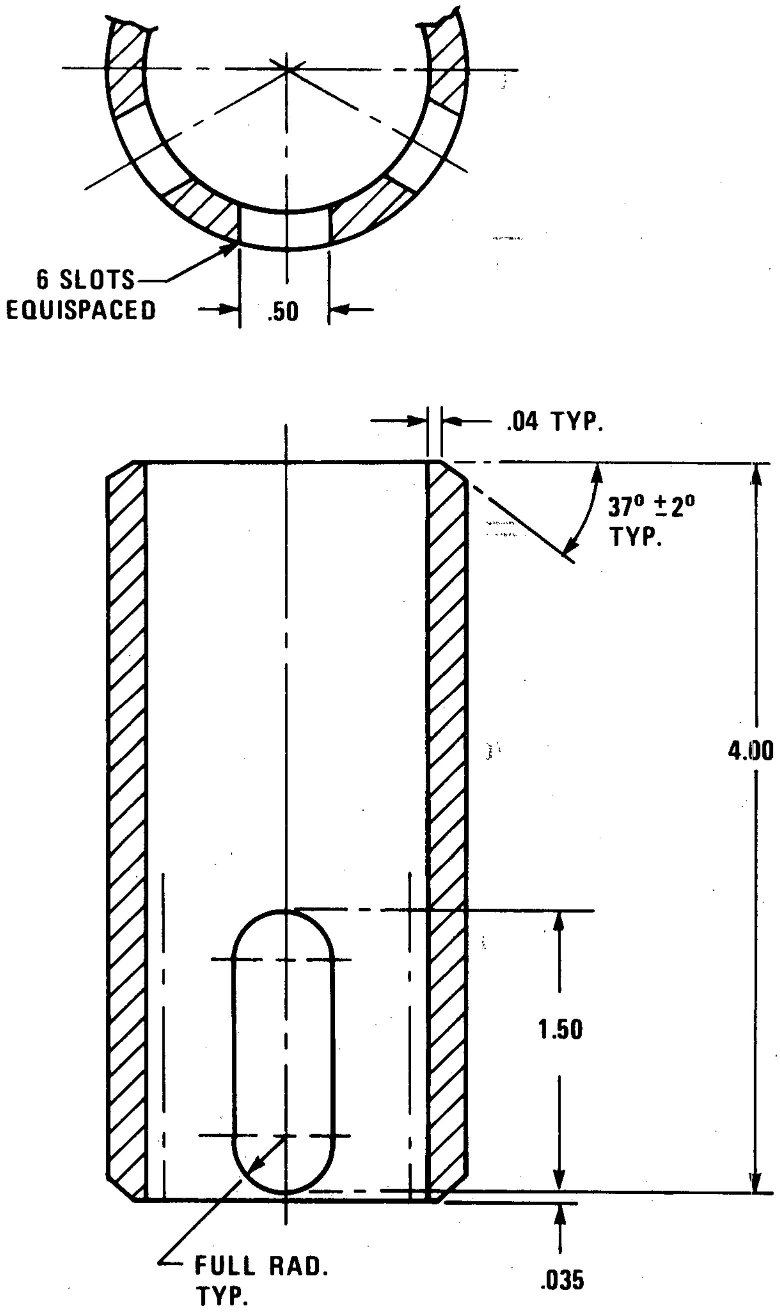


Figure A-1. Water Feed Concentration – Time Dependence in "Equivalent" Fast Sodium Removal Processes

APPENDIX B

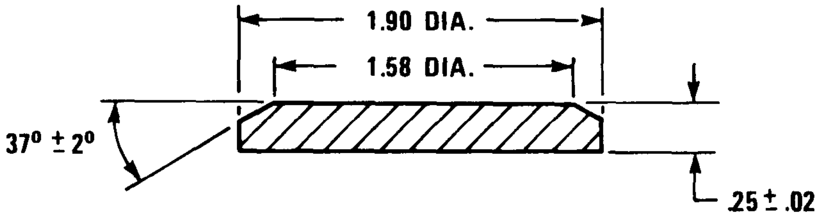
ARD MANUFACTURING SKETCHES FOR TEST MODEL FUEL SUBASSEMBLY



MATL: TYPE 316 S.STL.
1½" PIPE (1.90/D x 1.51/D)
SCHED. 80

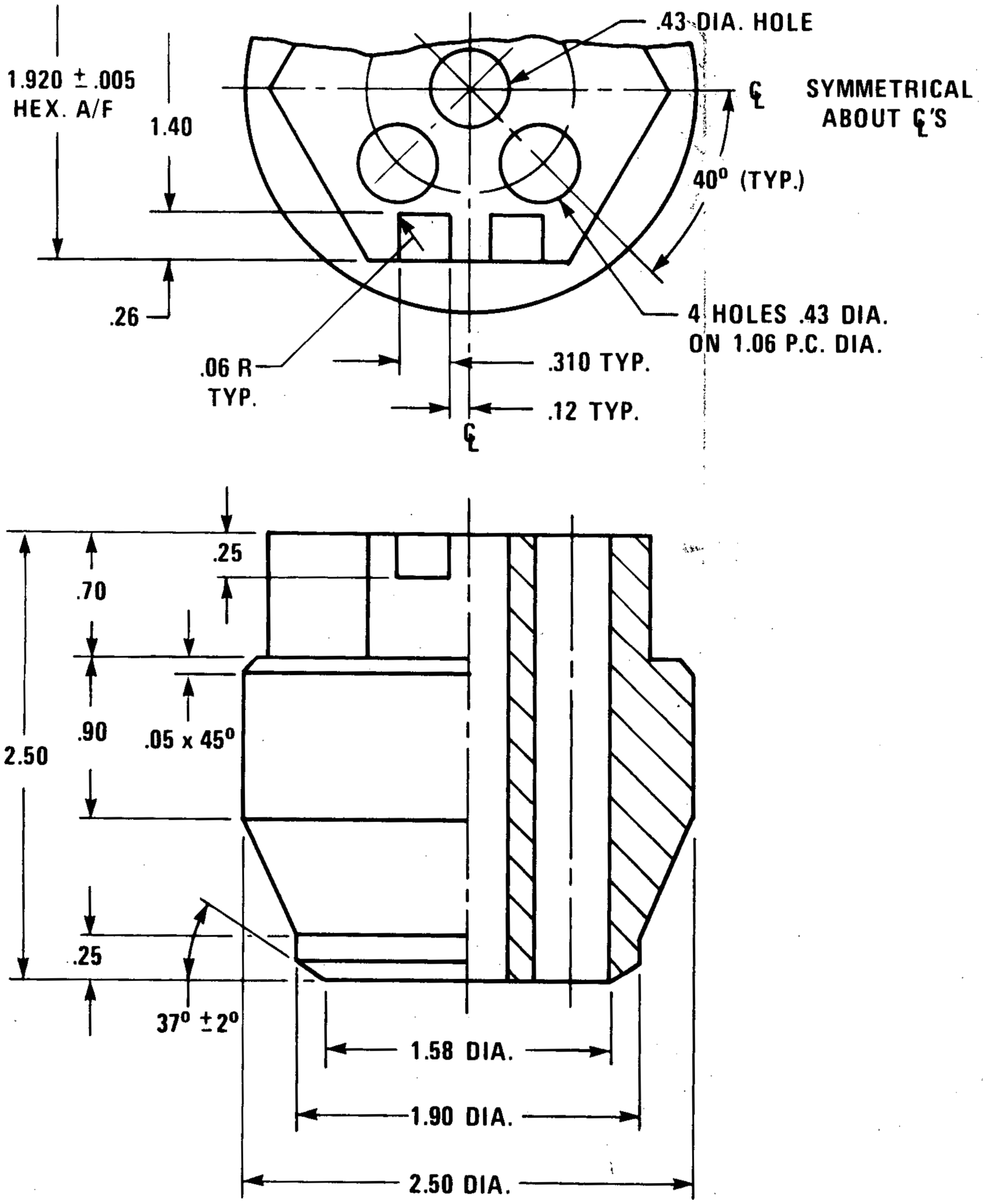
TOL: ± .010 UNLESS STATED

Figure B-1. Inlet Tube, ARD-SK #0482



MATL: 316 S. STL.
TOL: ± .10 UNLESS STATED

Figure B-2. Plate, ARD-SK #0483



MATL: 304 S.STL.
TOL: ±.01 UNLESS STATED

Figure B-3. Body, ARD-SK # 0484

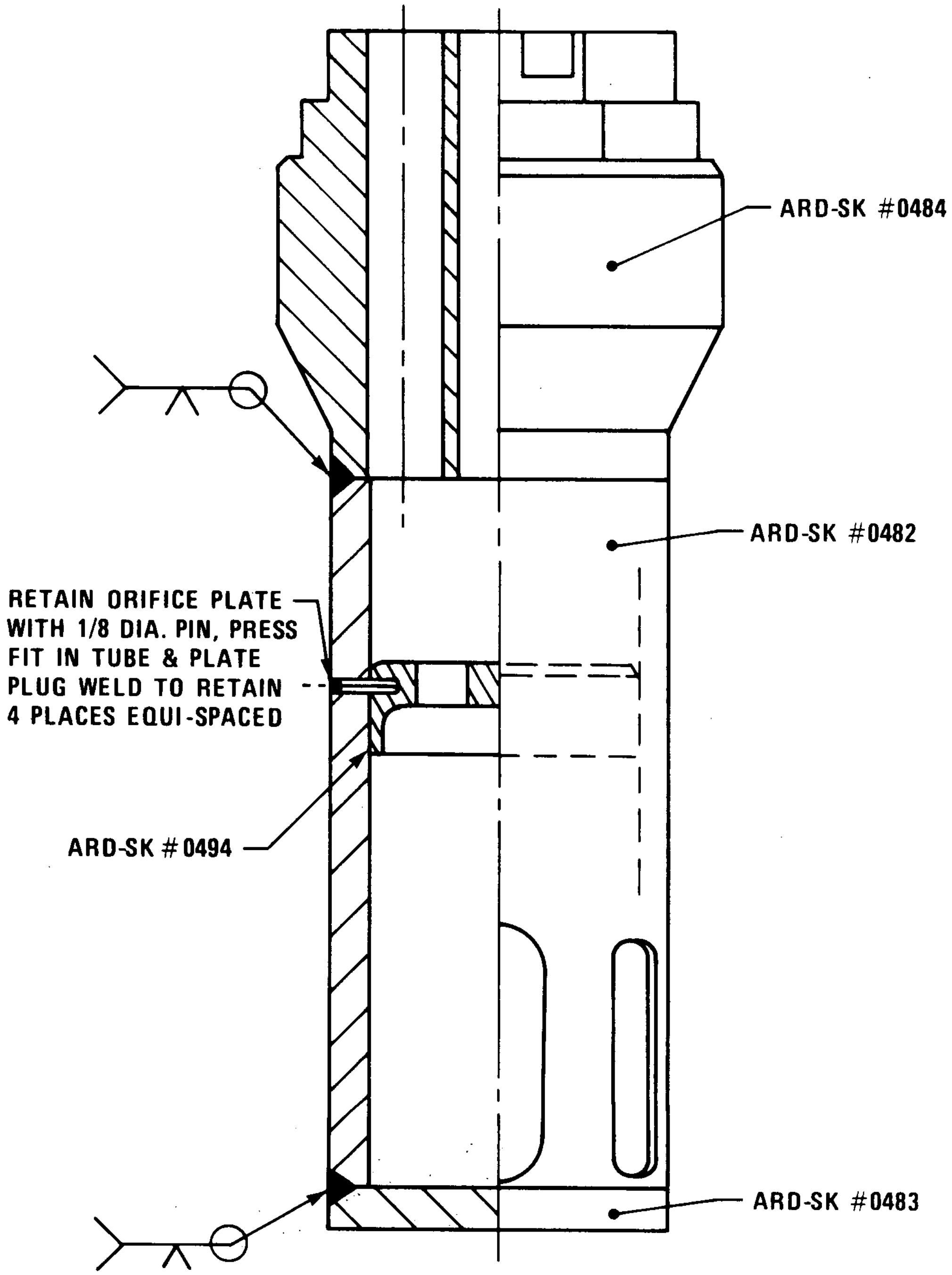
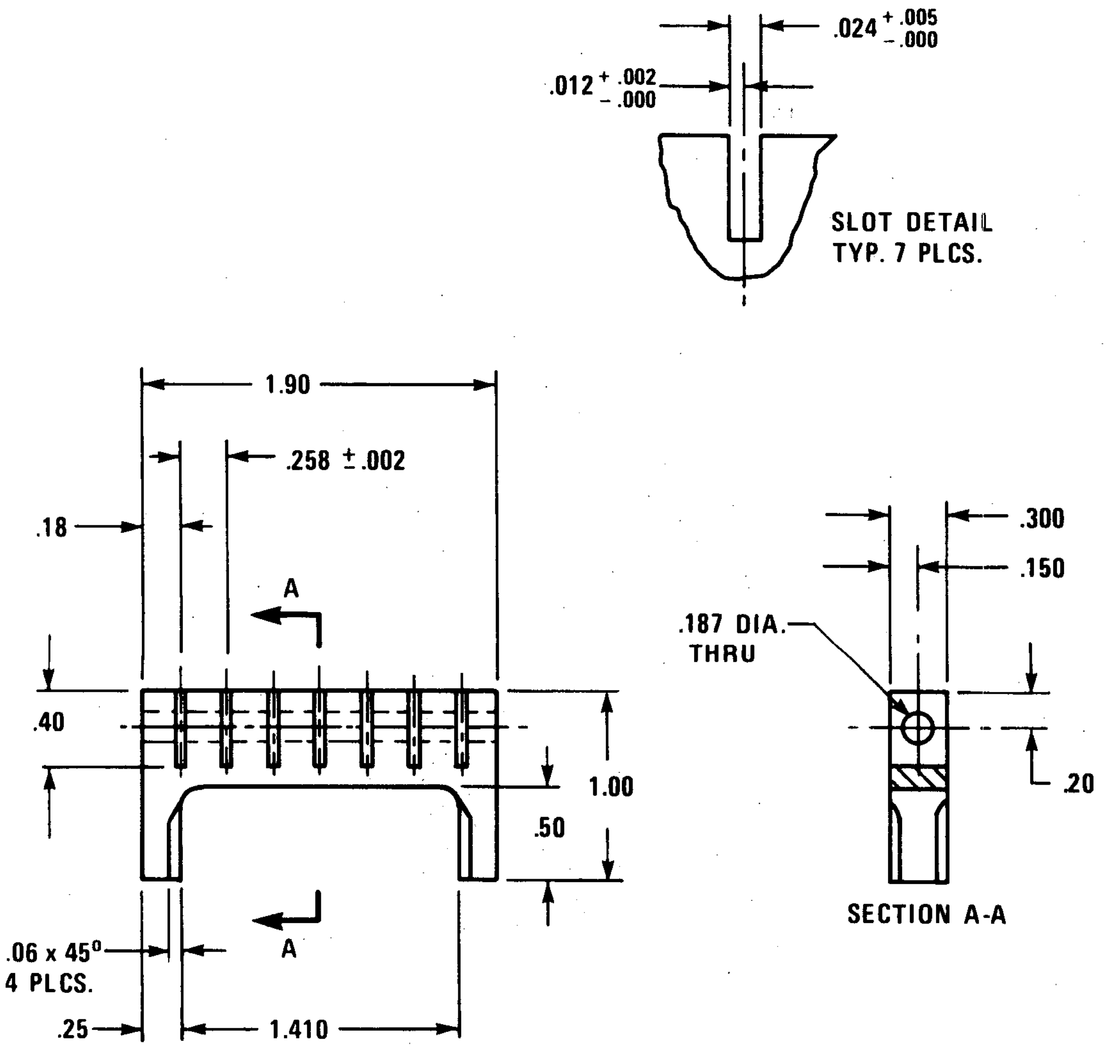
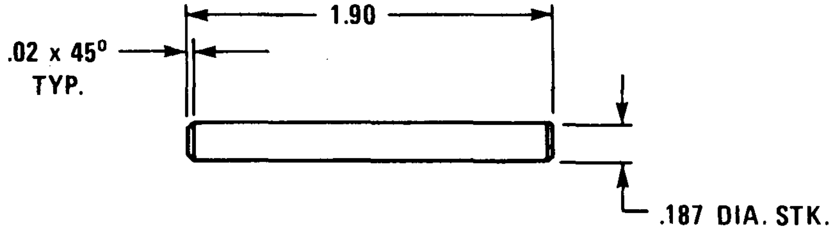


Figure B-4. Inlet Assy. ARD-SK #0485



MATL: 304 S.STL.
TOL: ±.01 UNLESS STATED

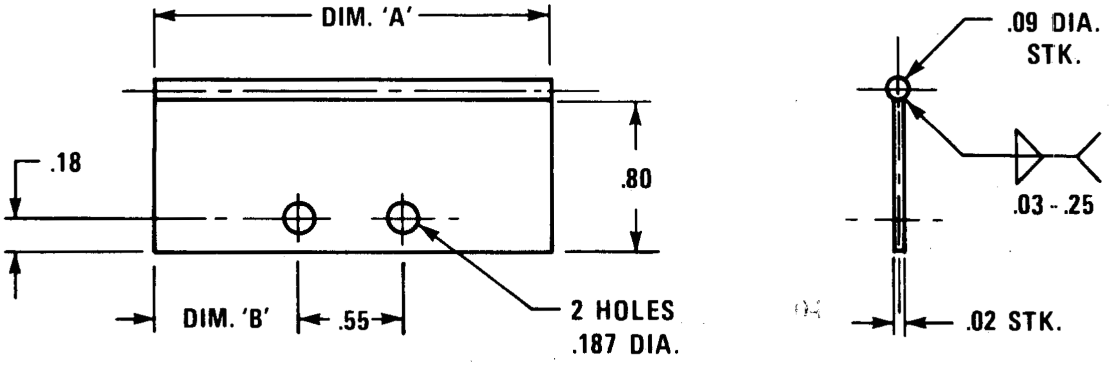
Figure B-5. Support Bar, ARD-SK #0486



MATL: 304 S. STL.
TOL: ± .010

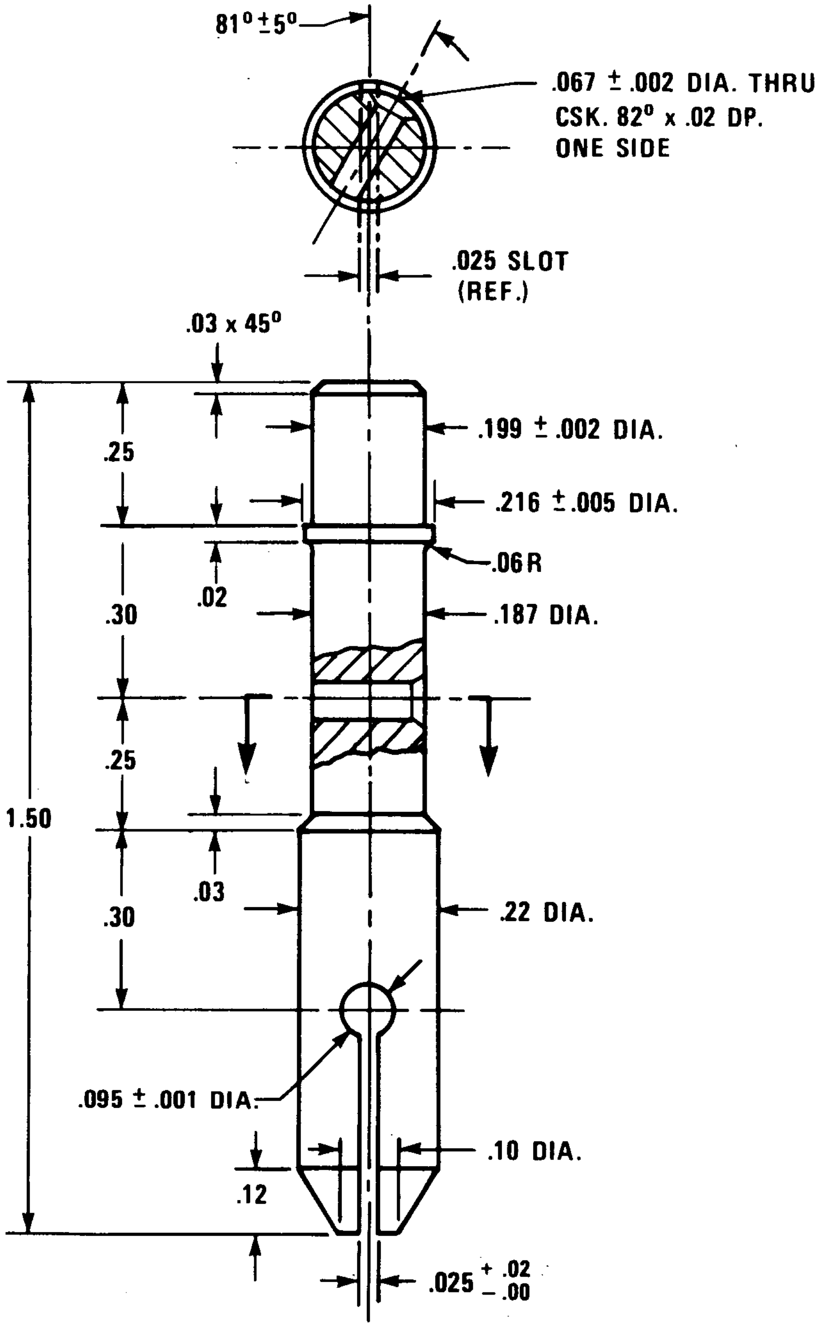
Figure B-6. Locking Pin, ARD-SK #0487

ITEM #	DIM. 'A'	DIM. 'B'	NO. REQ'D. PER ASSY.
ARD-SK 0488 - 1	2.10	.78	1
0488 - 2	1.80	.62	2
0488 - 3	1.50	.48	2
0488 - 4	1.20	.33	2



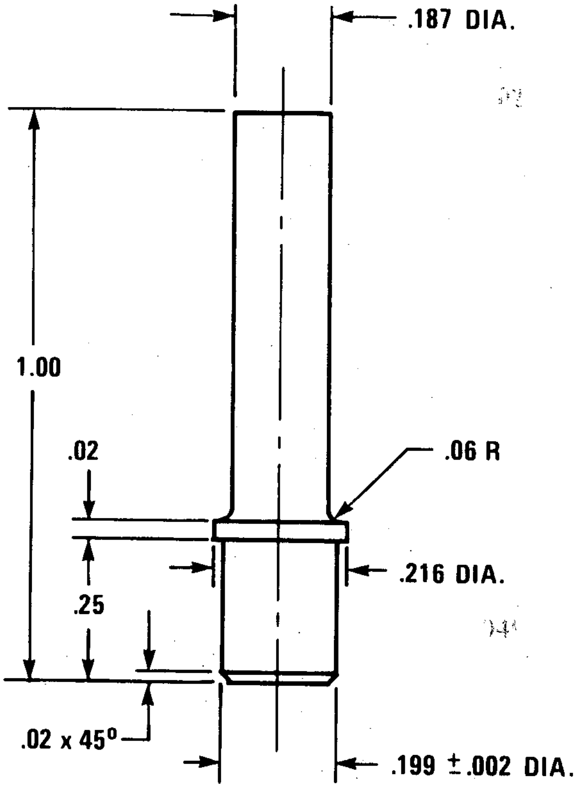
MATL: 316 S. STL.
TOLS: ± .01 UNLESS STATED

Figure B-7. Attachment Rail, ARD-SK # 0488



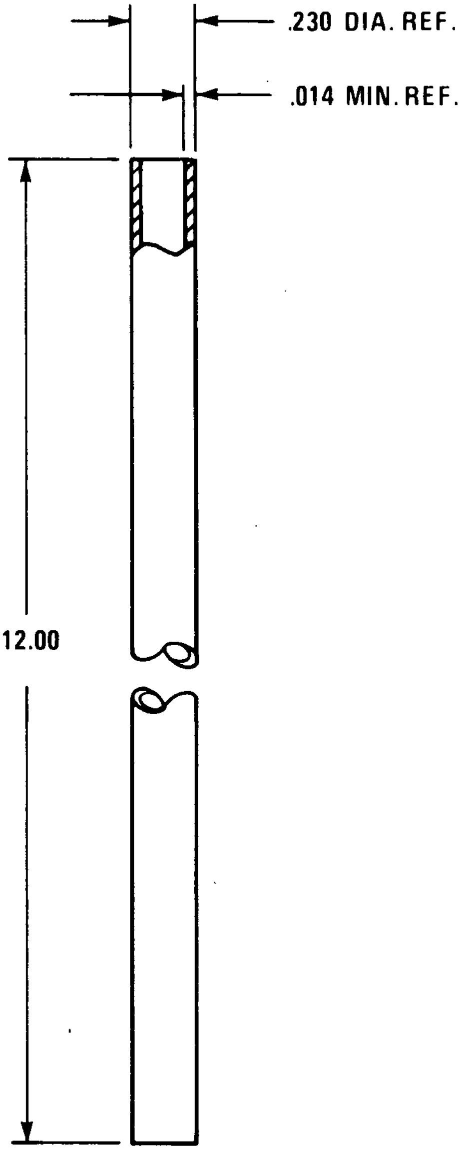
MATL: 316 S. STL.
TOLS: ± .01 UNLESS STATED

Figure B-8. Bottom End Cap, ARD-SK #0489



MATL: 316 S. STL.
TOLS: ± .01 UNLESS STATED

Figure B-9. Top End Cap, ARD-SK #0490



MATL: 316 S. STL.
20% COLD WKD.

TOL: ± .02

Figure B-10. Cladding, ARD-SK #0491

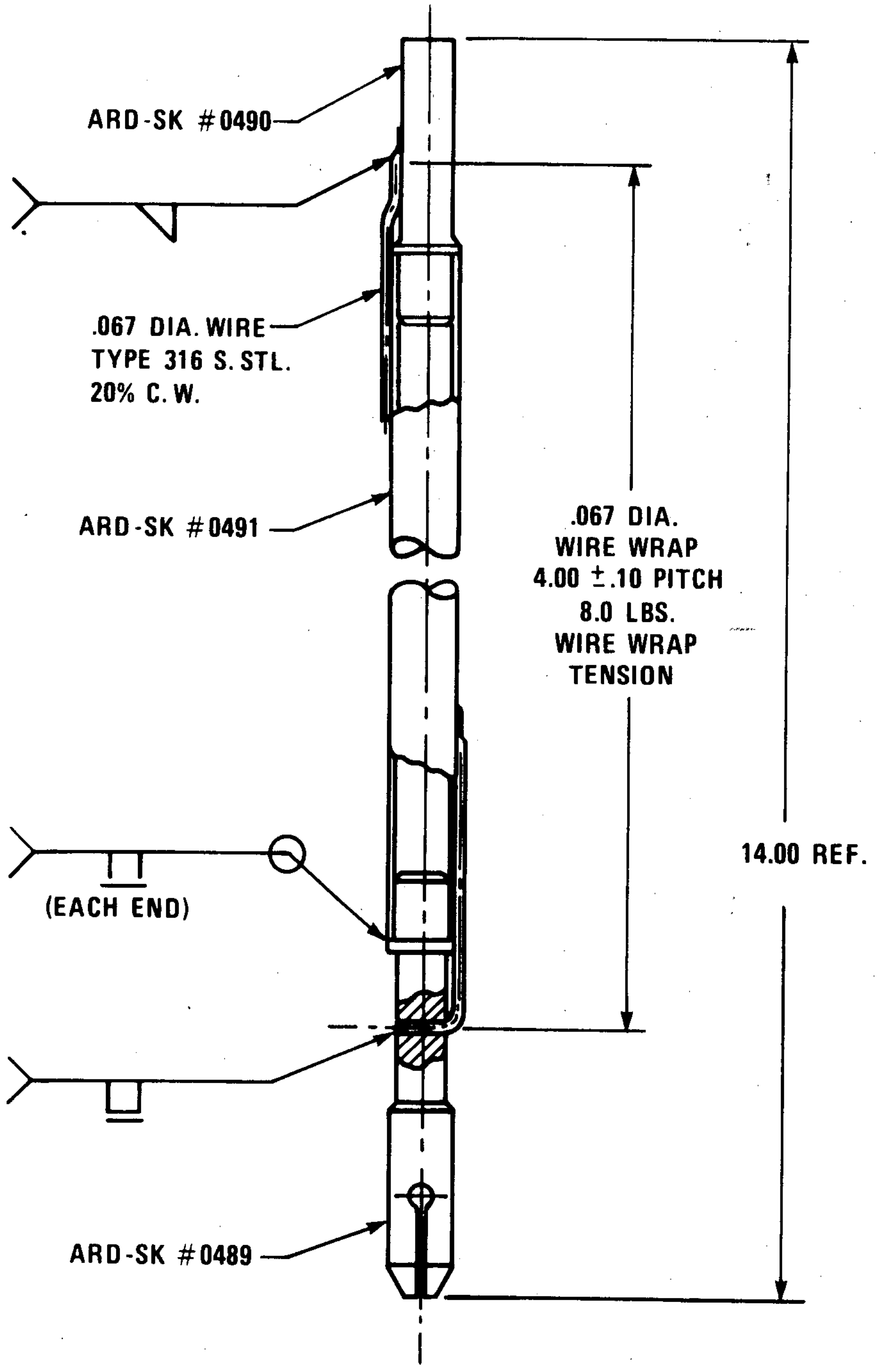
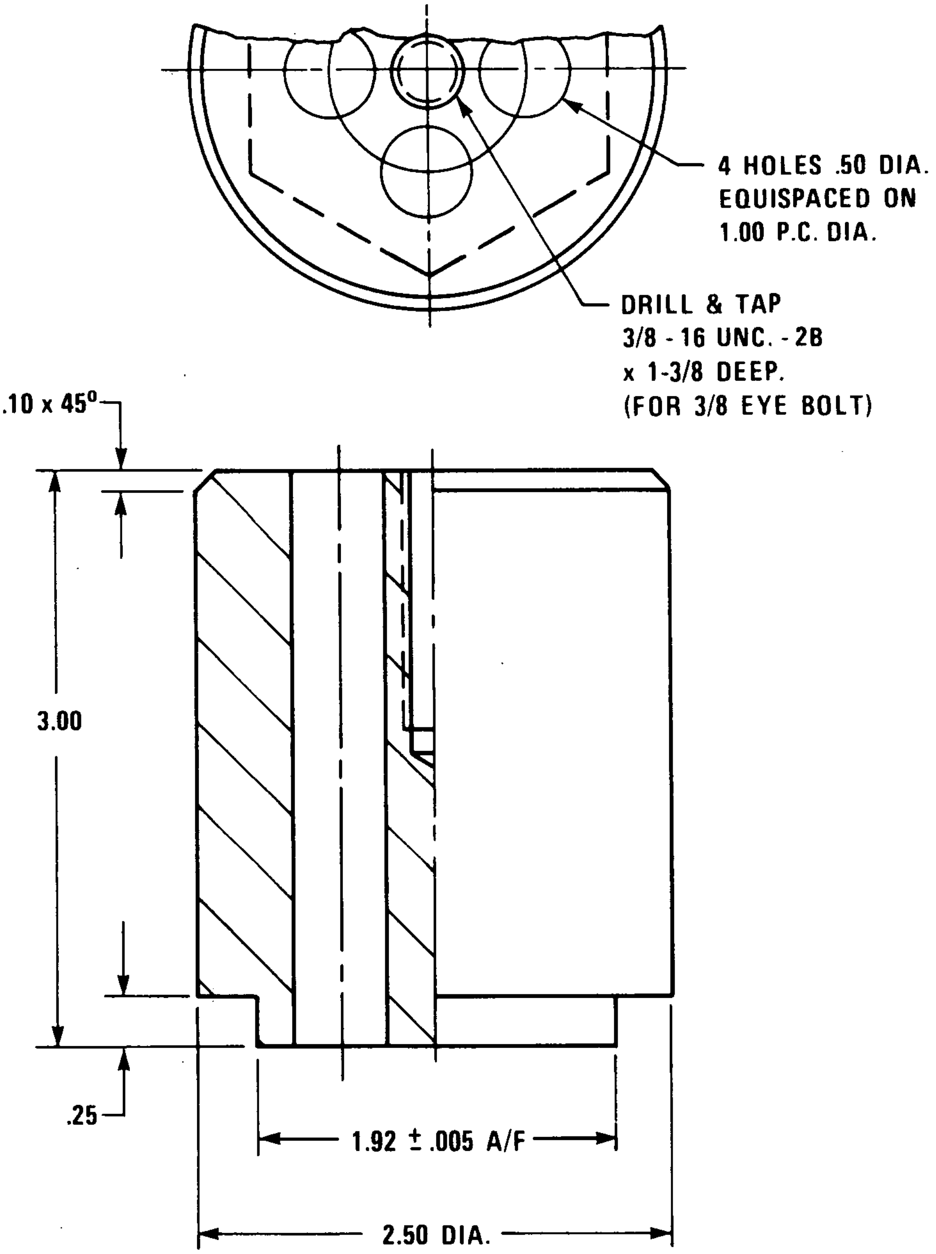
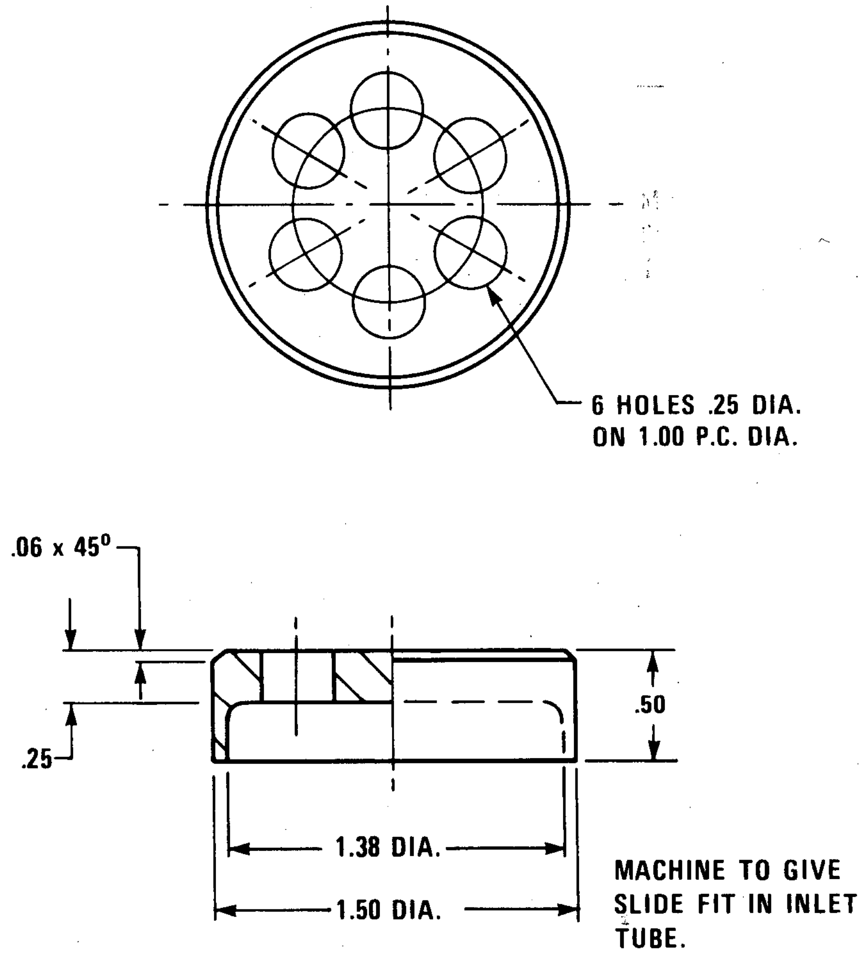


Figure B-11. Fuel Rod Assy., ARD-SK #0492



MATL: 304 S. STL.
TOL: ± .01 UNLESS STATED

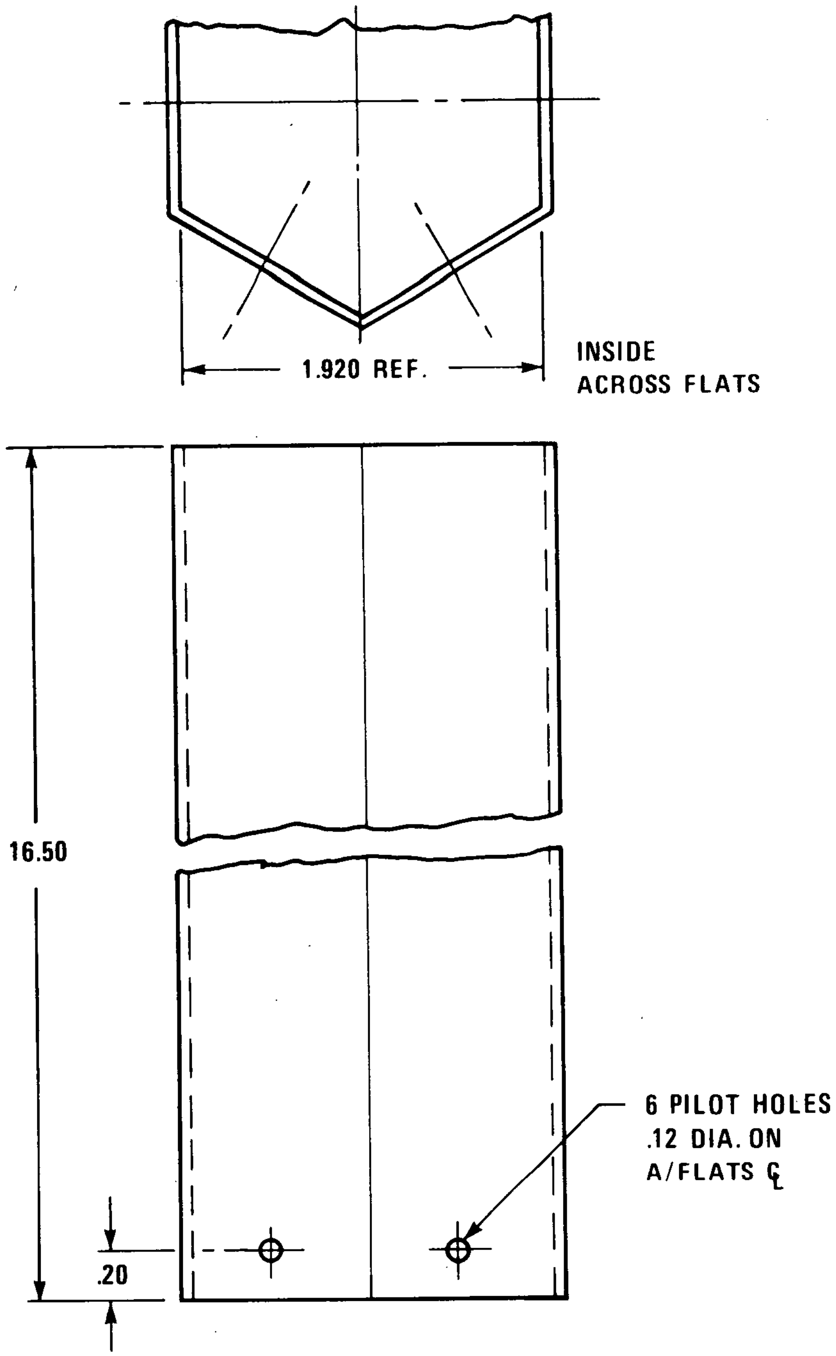
Figure B-12. Handling Socket, ARD-SK #0493



MATL: 304 S.S.
1.5 DIA. BAR

TOL: ± .01

Figure B-13. Orifice Plate, ARD-SK #0494



MATL: 304 S. STL. HEX TUBE
(P.O. # 107991 IT. 2)

TOLS: ± .01

Figure B-14. Duct, ARD-SK #0495