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FFTF
FUEL ASSEMBLY NOZZLE
DEVELOPMENT TESTING

Hanford Engineering Development Laboratory

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R. B. Richman
O. S. Fiskum

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August 1976

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FFTF FUEL ASSEMBLY NOZZLE DEVELOPMENT TESTING

R. B. Richman and O. S. Fiskum

April 1974

I. INTRODUCTION

A salient feature of each LMFBR core component assembly, whether it be driver fuel, control rod, or test assembly, is the nozzle at the lower (inlet) end of each assembly. Whenever the reactor is fueled, each nozzle must rest, with relatively small clearance, within a mating receptacle in the reactor core support plate. For some reactor designs, an intermediate liner forms part of the receptacle assembly to provide a relatively long-life wear-resistant surface. Refueling operations involve movement of the nozzle out of its close-clearance repository as the fuel assembly is withdrawn from the core. When the replacement fuel assembly is inserted, its nozzle then fits into this close-clearance region.

The core assembly nozzle-receptacle combination is designed to perform three primary functions:

1. Provide guide and bearing surfaces for desired spacing and support of the core assemblies.
2. Direct and distribute the sodium coolant flow upward throughout the core region of the assembly in the desired proportions.
3. Control the distribution of a very small proportion of flow exterior to the core assembly to maintain the desired hydraulic balances and supply minor cooling to ex-core and sub-core regions, while maintaining primary distribution of coolant into the core assembly as indicated above.

The objective of this nozzle insertion and removal test program was to determine the design characteristics required for satisfactory performance of at least one FFTF fuel nozzle and piston ring design in a prototypic sodium environment. Relatively easy installation and fully satisfactory flow performance of the close-clearance nozzle-receptacle combination is considered to be assured for a new fuel assembly during early periods of reactor operation. However, this combination must continue to provide adequate flow distribution and must be removable without excessive forces, even after some creep and/or swelling distortion of the assembly and its immediate neighbors has occurred as a result of long-term exposure of the stainless steel components to the intense nuclear radiation in the reactor core. The testing described in this report was performed primarily to determine the axial and lateral (load pad) forces involved in assembly withdrawal and the wear characteristics of nozzle and liner surfaces as affected by these variables:

- Creep and swelling distortion (resulting in various bowing configurations for the hexagonal duct portions of the fuel assemblies), (1)
- Various configurations of the load pads of adjacent assemblies (as produced by distortion of the assembly ducts and by the extent of applied core restraint), and
- IVHM grapple alignment tolerances.

The original test objective was limited to design verification by nozzle insertion and withdrawals in an air environment. Initial tests with straight or stepsided nozzles, and large nozzle-to-receptacle contact area, revealed the need for significant changes in nozzle design to preclude the occurrence of excessive forces and wear damage during withdrawal of bowed fuel assemblies. Results of this initial testing, previously reported informally, are included (Appendix B). The objectives of the subsequent test program, incorporating improved designs of nozzle-receptacle-liner combinations, were amplified to include final testing in sodium after performance of a substantial parametric study in air. The first nozzle design iteration consisted of an articulated unit (Appendix C). Test articles of this design were fabricated and used for alignment of the test equipment. Withdrawal tests were not performed with the articulated design, however, because the nozzle design concept was changed prior to completion of test preparations.

A series of tests were performed in an air environment with an early (4 piston ring) version of the FFTF nozzle-to-liner reference design. Results from these tests, included with the test article description in Appendix D, were used to define the boundary conditions for the subsequent parametric study with the final reference design of FFTF nozzle-to-liner interface.

II. SUMMARY

Five major designs of fuel assembly nozzle were evaluated in this test program to determine withdrawal characteristics. Nozzles of 316 SS or chromium-plated SS surface were used in contact with Inconel 718 liners (the initial test series used a 304 SS receptacle with no liner-see Appendix B). Tests were run in air and in 400°F hi-purity sodium. The occurrence of wear, and material transfer on nozzle, piston ring, or liner surfaces, as well as axial withdrawal forces and lateral forces at load pad and liner-receptacle regions, were determined as a function of several parameters:

- Nozzle design,
- Nozzle surface material,
- Deflection of the fuel assembly duct-produced by creep and/or swelling distortion,

- Deflection of adjacent load pad configurations produced also by creep and/or swelling distortion.
- IVHM grapple misalignment.

Testing in both the sodium environment and in air showed that a chromium-plated fuel assembly nozzle with a single upper piston ring and a lower close clearance region in an Inconel 718 receptacle liner provided superior resistance to nozzle wear damage, and did not cause damage to the long-life liner. Moderate, but acceptable, withdrawal forces were measured for removal of some fuel assemblies under conditions simulating the effects of extended period of operation in the intermediate rows of the FFTF reactor core. Some lateral forces were also applied between the load pads of adjacent fuel assemblies, and between the nozzle and its liner, but in all withdrawals of the proposed nozzle design these forces were well below those which could interfere with satisfactory withdrawal.

A number of nozzle-liner-receptacle designs were studied in this test program in conjunction with the major test parameters of fuel assembly duct bow, adjacent assembly configuration, and grapple alignment tolerance. Analysis of results, as the testing progressed, contributed to development of the optimum FFTF nozzle-liner-receptacle design.

III. TEST EQUIPMENT

A. Test Fixture

The test fixture for fuel assembly nozzle testing was designed and fabricated at HEDL (Figure 1). The frame is constructed mainly of 2 1/2 inch Schedule 40, Stainless Steel pipe, and 1 inch thick Stainless Steel plate, rigidly braced and bolted to the floor. The fixture includes:

The simulated core support plate at reference elevation "0" which supports the fuel assembly nozzle, liner, and receptacle.

A 1-inch plate located at the center of the fuel assembly above-core load pads (elevation 81 inches with fuel assembly fully inserted), with six linear (dovetail) slides and load cells mounted in a hexagonal pattern.

A 1-inch plate located at the center of the fuel assembly top load pads (elevation 129 inches with fuel assembly fully inserted), with six linear (dovetail) slides and load cells mounted as above.

An adjustable guide plate at elevation 169" which simulates IVHM constraint.

A removable plate at the top (elevation 222") which supports the 2-ton electric hoist.

A simulated FFTF fuel element was used for each test, with a nozzle attached to the bottom end of the element and a load cell and eye bolt at the top for hoist connection. The 2-ton capacity electric hoist was used to raise and lower the fuel assembly in the simulated core. Linear dovetail slides and load cells, mounted at the fuel element load pad elevations, were used to simulate neighboring fuel elements. The slides were adjusted to simulate relaxing of the core, skewing of the core, or other configurations that may be encountered during discharge of the fuel from FFTF. Further description of the simulated fuel assemblies, methods used for preboring these assemblies, and the positioning of the adjacent load pads, are described below. "As-built" dimensions and bow configurations are in Appendix E.

The core receptacle, containing a liner of Inconel 718 alloy, simulated the FFTF configuration. During air testing, a load cell was attached at the bottom end of this receptacle, four load cells were attached at 90° intervals around the receptacle at 1 inch from the top (Figure 2), and four more load cells were attached at 90° intervals around the receptacle at 19 inches up from the bottom (Figure 3). These cells sensed loads on the receptacle during insertion and withdrawal of the various test fuel assemblies. Dial indicator gages were also employed to measure deflection of the receptacle and liner during insertion and withdrawal of the fuel assemblies.

Early in the program (July 1970) tests were conducted on the initial designs of fuel element nozzle, liner and receptacle. The test hardware was minimal (Figures 4 & 5). Test description and results are in Appendix B. The nozzle, liner and receptacle design was changed considerably from the initial design as a result of information obtained during initial testing.

B. Simulated Fuel Assemblies

Each simulated FFTF fuel element consisted of a hexagonal stainless steel shell with typical load pad surfaces and containing a steel ballast for a total weight of 405 lbs. Nozzles with prototypic FFTF dimensions were threaded onto the bottom end of each test element. Both bare 316 stainless steel and chromium plated nozzle surfaces were tested; these materials are satisfactory for use in flowing sodium at temperatures to at least 845° F.,⁽²⁾ and were the primary choices for the FFTF nozzles. The test assemblies initially included a rigid top load pad and handling socket at the top; early in the test program, the assemblies were modified to a "sliding collar" with tungsten-carbide coating at the top load pads (above-core load pads remained rigid and with the original aluminum oxide coating).

Four configurations of fuel assemblies were used, simulating selected conditions expected during long-term FFTF reactor operation. The centerline displacement pattern, shown (graphically) in Appendix E, is described below:

1. New, straight fuel, designated B_0 .
2. Creep distortion after 3 reactor cycles, bowed across hexagonal flats, resulting in a top-to-centerline displacement of 0.248", designated B_1 .
3. Swelling distortion after 3 reactor cycles, bowed across hexagonal points, resulting in a top-to-centerline displacement of 0.457", designated B_2 .
4. A revised configuration of swelling dominated distortion after 4 reactor cycles, still bowed across points, but resulting in the greater top-to-centerline displacement of 0.942", designated B_2 .

Bending to simulated swelling and creep distortion in these test assemblies was applied in the pure bend fixture⁽³⁾ shown in Figure 6. (Neg-73 H0264-11) A uniaxial load was applied with the fixture to subject the assembly to a constant bending moment between the clamping blocks. Strain gage data were used as a guide, with center deflection measured directly at selected intervals during the bending (relaxation of the loading was required, of course, prior to measuring deflection). Measured centerline values for actual bends obtained by this method are included in the graphical representations of Appendix E.

C. Adjacent Load Pads

The test load cells, representing the adjacent fuel assembly load pads at both top and above-core elevations, were positioned into four configurations for these tests. Details of positioning for these simulated pads are shown (pictorially) in Appendix E:

1. A modified creep dominated core under passive restraint, providing small clearance at the top load pads, but relatively large clearance at the above-core load pads, designated A_1 .
2. A swelling dominated core under passive restraint providing large clearance at the top load pads, moderate clearance at the above-core load pads, but with the top load pad opening significantly displaced in the direction of free assembly bow, and designated A_3 (each top pad is displaced a different amount, but limiting pads are moved 0.132" to 0.164" in the free bow direction).

3. A swelling dominated core under active restraint, released 0.050", designated A_{3m}.
4. A swelling dominated core under active restraint, released 0.410", designated A_{5m}.
5. Configurations used in earlier tests, designated A₀ through A₆, are also shown in Appendix E and referenced in Appendix D.

D. Simulated IVHM Grapple Constraint

The available constraint and misalignment expected for the FFTF In-Vessel Handling Machine (IVHM) were simulated with a 1/2" diameter bar (or cable) through an adjustable guide. A conventional 2-speed electric hoist with encoder was connected to the simulated fuel assemblies by this bar, an eye bolt, and the load cell bolted to the top of the assemblies, as indicated in Figure 1. The bar (or cable) centerline was adjusted from true alignment to greater than 0.250" misalignment in various directions from the receptacle centerline, (i.e. the straight fuel assembly centerline) by means of the guide plate. This guide includes a circular plate fastened to the test fixture frame with equally spaced bolts to provide 6 angular positions. In addition, selected bolt holes are elongated to provide limited linear adjustment. Scribed marks at 120° intervals permit exact re-positioning of the guide after change-out of each fuel assembly. A split collar, adjusted with jack screws and lock nuts along a channel on the guide plate, provides an opening with 0.005" annular clearance to guide the withdrawal bar or cable. Simulation of IVHM positioning ("R-B" directions) and pull capability are precise with this hoist and guide plate; however, grapple compliance, push capability, and speed (hoist = 30 inches per minute; IVHM = 18) are only approximate.

E. Equipment Exclusive to Sodium Phase Testing

The lower section of the air test rig was later modified to provide immersion of the core receptacle, liner and the nozzle portion of the fuel assembly in 400°F sodium (FFTF shutdown parameter) during insertion and withdrawal of the fuel assemblies. The core receptacle and liner were fitted into a vessel made from 8 inch OD, schedule 160, stainless steel pipe. Grayloc hubs, welded to the vessel, allow parting of the upper and lower sections for inspection and replacement of the nozzle and liner. A bellows assembly is attached to the upper section of the vessel. The bellows section is constructed to allow

removal (unscrewing) of the fuel assembly from the nozzle and installing another fuel assembly while maintaining a barrier between sodium and the atmosphere (Figure 7). The vessel has an inlet connection at the bottom and an outlet at the top for sodium fill, drain and recirculation. The connection at the top also serves as an argon inlet for cover gas and purging. The bellows has a 14 inch stroke which allows the nozzle to be inserted and fully withdrawn from the liner during testing. The sodium vessel is equipped with heaters and thermocouples for temperature control and is rigidly supported in the test rig with alignment dowels to assure centering and leveling. The vessel can be removed from the test rig for filling or draining of sodium and disassembly for cleaning and inspection. After assembly in the 309 maintenance shop clean room (Figures 8 & 9), the vessel was helium leak checked (passed $<2 \times 10^{-7}$ std. atm/cc); heaters and thermocouples were then installed on the exterior. The assembled vessel was moved to the 335 Building and connected to the Small Components Evaluation Loop (SCEL) for sodium fill (Figure 10). A 50 psig helium pressure test was performed on the vessel and all connections to the vessel (no detectable leakage). Before sodium fill, a vacuum (<1 mm of Hg) was maintained on the vessel at 750° to 800° F. for 24 hours to draw off impurities. One gallon per minute of sodium at 800° to 1000° F. was then circulated through the vessel until the oxygen content of the sodium was less than 3 ppm

The sodium level in the vessel was adjusted to 41 inches (top of liner is 33 7/8 inches) and then the vessel was valved out from the sodium loop (SCEL). Argon cover gas at 2 psig was maintained in the vessel. The vessel was cooled to ambient, disconnected from the sodium loop, moved into the 336 Building, and installed into the test fixture.

F. Instrumentation and Control

Instrumentation used during air-phase testing included the following items (for model and serial numbers see Instrumentation Listing in Appendix F):

1. A commercial load cell, 0-5,000 lbs. tension - compression range, mounted on top of the simulated fuel assembly to measure vertical insertion and removal forces.
2. A digital encoder, attached to the electric hoist, to measure test elevation.

3. Eleven HEDL fabricated, double-cell, load sensors mounted on dovetail slide assemblies at each of the above-core load pad and top load pad elevations, to measure lateral forces from the simulated fuel duct during insertion and removal.
4. A linear potentiometer with 16 inch travel, attached to the duct wall, to provide supplementary elevation measurements.
5. Nine commercial load cells, positioned around the core receptacle, to measure lateral and vertical loads.
6. Signal conditioning equipment, two recording oscilloscopes and an X-Y plotter.

During testing, the signals from the encoder and from the load cell at the top of the fuel assembly were recorded on an X-Y plotter to provide permanent records of vertical forces as a function of assembly elevation. The signals from the HEDL fabricated load cells, the commercial load cells on the receptacle, and the 16 inch linear potentiometer were recorded on two oscilloscopes to provide a permanent record of lateral forces and vertical forces as a function of assembly elevation.

Instrumentation used during sodium-phase testing included all instruments listed for the air-phase testing except the nine load cells used around the core receptacle. Additional instrumentation used during sodium-phase testing included the following:

1. One temperature indicator-controller and two rheostats to monitor and control power to the test vessel heaters.
2. One temperature recorder to record the signals from the test vessel thermocouples and provide a permanent record of critical temperatures.
3. A pressure regulating valve to maintain a 5 psig argon cover gas in the test vessel.
4. The instrument control cabinet also contained a safety circuit to sound an audible alarm and shut off electrical power to all the vessel heaters if any of the following conditions occurred.
 - a. Argon cover gas pressure exceeded 25 psig.
 - b. Argon cover gas decreased to 2 psig.
 - c. Any thermocouple indication exceeded 500° F.

IV. TEST DESCRIPTION

Before a simulated fuel assembly was installed in the test fixture, all other test components were aligned. The core receptacle and liner were installed and checked for level and centering in the assembly. A chalk line with a plumb-bob on the end was strung through the center hole in the simulated IVHM guide plate. The plumb-bob was lowered until its tip was flush with the top of the receptacle liner, the simulated IVHM guide plate was adjusted until the plumb-bob was at exact center of the liner, then the guide plate was bolted in place. The guide plate was scribed at 120° positions to allow removal of the guide plate from its holder and ensure replacement in its exact position. Removal of the guide plate was required to install a fuel assembly. The load cells, mounted on dovetail slides at the above-core load pads and at the top load pads, were adjusted using the chalk line as centerline. A specially fabricated tool, having the exact dimensions of fuel element load pads and a centering mark to gage on the chalk line, was used to adjust the load cell dovetail slides to represent the positions of neighboring fuel elements in a compact core. The dovetail slides are a precision slide and their movement is read out in 0.001". The position of the dovetail slides was recorded for the centerline position of the compact core. The slides were then retracted to simulate a relaxed core and to allow installation of the fuel assembly. The simulated IVHM guide plate was removed and the simulated fuel assembly was installed. The IVHM guide plate was reinstalled to its scribe marks, the load cell was mounted on top of the fuel element, and connections to the hoist were then completed.

The test load cells, instrumentation and recording system was calibrated per approved HEDL procedures (See Appendix F).

For all tests the fuel element was inserted and withdrawn at 30 inches per minute. The travel of the fuel element from fully inserted to the fully withdrawn position was 14 inches. Various test conditions were established by adjusting the simulated IVHM guide plate, adjusting the dovetail slides to various core configurations, and using straight or bowed fuel elements.

During sodium-phase testing, the vessel internal temperature was maintained at 400° ± 5° F. (FFTF shutdown temperature). The instrument control cabinet was mounted on a dolly, and the instrument cables were attached with plug-in connectors, so that the cabinet was readily moved between the sodium fill location (SCEL) and the 336 Building test location. Electrical power was supplied to the sodium vessel through this control cabinet, and temperatures, cover gas pressure, and safety circuits were monitored at all times with this unit.

V. RESULTS

Significant results from testing of chromium-plated and bare stainless steel nozzles in a 400° F. sodium environment are compared in Table I and Figure 11. Additional test data are listed in Appendix A. Maximum vertical withdrawal loads of 1090 to 1370 pounds were measured during 30 withdrawals in sodium for a chromium-plated nozzle on a simulated 4-cycle swelling dominated fuel assembly, when withdrawn from a configuration representing a swelling-dominated core under passive restraint. For the bare stainless steel nozzle under identical conditions, vertical withdrawal loads showed maximums from 1360 to 1645 pounds, with a relatively steady increase as testing progressed to 30 withdrawals. Lateral load vectors at both the top load pads and the above-core load pads were comparable for both stainless steel and chromium-plated nozzles, as shown in Table I and Figure 11. Maximum withdrawal loads for these 30 withdrawals are also shown in the graph at the lower left side of Figure 12. Also visible in Figure 12 are the nozzle surfaces after completion of the 30 withdrawals.

The chromium-plated surface was essentially undamaged; significant wear and scratching occurred at three places on the 316 stainless steel surface, with major wear in the region 2 inches to 4 inches from the nozzle tip. This nozzle region, designed to provide controlled sodium "leakage" through a small annular clearance between this surface and the adjacent liner surface, is shown in greater detail in Figures 13 and 14 for the 316 stainless steel and the chromium-plated surfaces, respectively. Wear on these stainless steel surface appears similar to the type often described as adhesive, sliding wear. (4)

Earlier results from withdrawal tests in air with active core restraint, shown in Table II, indicate a similarity to those later found for the sodium environment with passive restraint. Withdrawal loads in air were within the same range (850 to 940 pounds) for single test cycles for both chromium-plated and bare 316 stainless steel surfaces. (when load pad surfaces were fully simulated with flat plates). However, the significant wear of the stainless surface (Figure 15) was in distinct contrast to the essentially undamaged chromium-plated surface (Figure 16).

The amount of core release, when active restraint is used, significantly affects both the withdrawal and adjacent lateral loads. This effect was verified in sodium tests. In air testing, the tightly held cores (0.050") showed 850 to 1370 pounds maximum withdrawal loads, whereas cores released 0.410 inches resulted in only 450 to 550 pounds maximum withdrawal loads, for comparable tests. Intermediate release of 0.200 inches (A_4 , A_{4m}) showed maximum loads of 670 to 890 pounds. Test data illustrating this effect are shown in Figure 17. The "sliding collar" configuration of top load

TABLE I

WITHDRAWAL LOADS FOR CHROMIUM-PLATED (Cr) AND EXPOSE 316 STAINLESS STEEL(S) CORES IN 400°F SODIUM

TEST CONDITIONS AND WITHDRAWAL CYCLE	WITHDRAWAL ELEMENT, INCHES	VERTICAL LOADS, POUNDS		LATERAL LOAD VECTORS (LBS-DEGREES)							
		Cr-Plt	SS	TOP LOAD PADS				ABOVE CORE LOAD PADS			
				Cr-Plt		SS		Cr-Plt		SS	
				Lbs.	°	Lbs.	°	Lbs.	°	Lbs.	°
CYCLE 1	0	0	0	610	344	554	350	705	158	725	177
B ₂ A ₃ M ₀ Swelling- dominated, 4-cycle fuel (B ₂); Swelling- dominated, passive- restraint core (A ₃); grapple at centerline (M ₀)	0.1	1055	-	607	344	-	-	691	157	-	-
	Max.	1370	1360	581	343	514	352	650	153	682	177
	Min.	(1415)*									
	(1" to 4")										
2	0	0	0	616	341	526	354	-	-	750	176
	0.1	965	-	606	342	-	-	551	154	-	-
	Max.	1090	1445	593	343	544	353	655	152	772	176
	Load	(1145)*									
5	0	0	0	699	344	533	344	521	137	819	180
	0.1	1010	-	625	343	-	-	541	150	-	-
	Max.	1090	1585	601	344	584	353	541	143	745	175
	Load										
10	0	0	0	639	342	526	344	567	143	872	179
	0.1	1070	-	652	340	-	-	577	151	-	-
	Max.L.	1185	1500	593	343	429	356	561	145	688	179
15	0	0	0	631	343	521	347	582	144	702	180
	0.1	1050	-	618	343	-	-	569	148	-	-
	Max.L.	1220	1575	600	343	486	352	577	146	629	174
20	0	0	0	641	342	508	345	557	144	727	179
21	0.1	1050	-	617	344	-	-	559	149	-	-
	Max.L.	1255	1575	581	344	474	354	556	145	651	174
25	0	0	0	662	343	514	346	525	137	708	180
	0.1	1065	-	613	344	-	-	582	151	-	-
	Max.L.	1370	1625	577	344	429	0	564	146	611	177
30	0	0	0	-	-	496	345	560	139	720	179
	0.1	1050	-	-	-	-	-	580	149	-	-
	Max.L.	1290	1645	-	-	544	354	587	145	770	175
B ₁ A ₁ M ₀	CYCLE 1	0	0	33	163	25	120	8	246	66	292
Creep- distorted, 3-cycle fuel (B ₁); Creep- dominated, Passive-restraint Core (A ₁); grapple at centerline (M ₀)	0.1	525	525	26	172	26	116	12	244	59	295
	Max.L.	590	585	30	195	15	133	5	270	5	300
10	0	0	0	38	163	45	112	5	270	76	283
	0.1	510	530	25	188	15	144	10	245	5	300
	Max.L.	540	555	37	195	5	191	5	270	5	300
25	0	0	0	39	170	28	88	5	270	61	277
	0.1	515	545	24	184	6	180	10	245	5	300
	Max.L.	560	570	29	194	10	264	5	270	5	300

* Slipper port coated with inner tube of 3.3 to 3.5 micron. Surface was lubricated, but no contact occurred after cycle 4.

COMPARISON OF LOADS FOR STAINLESS STEEL AND CHROMIUM-PLATED NOZZLES TESTED IN SODIUM

FIG. 11

~~24~~ (24)

FIGURE 13 : Stainless Steel Nozzle Tested in
Sodium ~~env~~ Environment
(Neg. 73-4490-1)

~~34~~ (36)

FIGURE ¹⁴~~12~~: CHROMIUM-PLATED NOZZLE
AFTER 30 WITHDRAWALS ~~TESTS~~ IN
SODIUM ENVIRONMENT.

(neg 73-5323-1)

pads was used in this test series. Earlier test results indicated that the sliding collar reduces side loading at the top load pads, as expected; although, no quantitative tests of sliding collar effects were included in this test program.

Comparable results were obtained for withdrawal tests in either air or sodium environment. As noted above, the significant surface damage to bare stainless steel and virtual absence of damage to chromium-plated steel, revealed in cyclic tests in air, was specifically verified by the tests in sodium. Withdrawal loads, listed at the top of Table III, were also similar throughout the withdrawal cycle for tests run specifically to compare values in air and sodium. Withdrawal test data in Section B of Table III provide further evidence of similar load values in either the air or sodium test environments. These Section B data are considered secondary to the specific comparison test data because of other differences in test conditions (as, for example, presence of chromium-plated vs bare stainless steel surface); however, since the effects of the other test conditions on load values have been characterized during numerous tests in this program, it is feasible to draw a valid comparison between the sodium and air environments from these data. Calculated ratios of load values measured in sodium to those measured in air are also listed in Table III, and indicate a range of 0.89 to 1.82, with an average ratio of 1.20.

With the present single-piston-ring nozzle design, withdrawal loads and lateral loads on adjacent pad surfaces were not significant for either the simulated creep distorted assemblies (B_1), or the simulated new, straight fuel assemblies (B_0). Data from numerous tests (listed in Appendix A) show withdrawal loads consistently less than 200 pounds in excess of the approximately 400 pounds assembly weight. Lateral loads on adjacent pads showed maximum vector loads of 101 pounds at the Top Load Pads (TLP) and 92 pounds at the Above Core Pads (ACLP). These insignificant loadings prevailed for even those situations with extremely close spacing of the adjacent top load pads (A_1). Relatively minor damage to either chrome-plated or unplated stainless steel nozzle surfaces noted in these tests is in contrast to significant galling and scratching of the earlier design (four piston rings) of unplated stainless steel nozzle in previous testing with creep distortion (B_1). See Appendix D for results of tests with the 4-ring nozzle design.

Relatively small differences in loads were measured when the hoist guide was moved to simulated IVHM misalignments of 0.200 or 0.250 inches. Table IV lists data from two series of these dis-alignment tests in air; one series used the swelling dominated assembly (B_2) with a relatively relaxed,

TABLE III

COMPARISON OF WITHDRAWAL LOADS FOR NOZZLE TESTS IN AIR AND SODIUM

TEST CONDITIONS (SEE TABLE II AND APPENDIX E)	WITHDRAWAL ELEVATION, INCHES.	VERTICAL WITHDRAWAL LOADS, POUNDS (INCLUDES ASSEMBLY W.T. OF P-X #10#)		LOAD RATIOS $\frac{\text{SODIUM}}{\text{AIR}} = R.$
		AIR	SODIUM	
SECTION A = DIRECT COMPARISON				
B ₂ A _{3m} (P) M ₀ - CYCLE 1 STAINLESS STEEL	0.4 1.2 4.9	835 850 530	1015 1150 965	1.22 1.35 1.82
B ₂ A _{3m} (P) M ₀ - CYCLE 2 STAINLESS STEEL	0.3 1.5 3.1	870 890 710	825 1005 800	0.95 1.13 1.13
SECTION B = OTHER COMPARATIVE DATA:				
B ₂ A _{5m} (P) M ₀	0.1 1.8 2.8	(CR-PLT) 510 470 435	(SS) 455 510 525	0.89 1.08 1.21
B ₂ A _{3m} P M ₀ CHROMIUM PLATE	0.7 2.8 4.0 4.3	820 750 503 875	- - - -	
B ₂ A _{3m} DPM ₀ CHROMIUM PLATE	0.2 0.6 2.4 3.0 4.4	860 900 940 815 858	- - - - -	
B ₂ A _{5m} DPM ₀ CHROMIUM PLATE	0.2 0.5 4.4	450 445 425	- - -	
AVERAGE RATIO (9 VALUES) = 1.20				

Moiz

= 50.25
1
1.22SECTION A = DIRECT COMPARISON
B₂ A_{3m}(P) M₀ - CYCLE 1
STAINLESS STEELB₂ A_{3m}(P) M₀ - CYCLE 2
STAINLESS STEELSECTION B = OTHER
COMPARATIVE DATA:B₂ A_{5m}(P) M₀B₂ A_{3m} P M₀
CHROMIUM PLATEB₂ A_{3m} DPM₀
CHROMIUM PLATEB₂ A_{5m} DPM₀
CHROMIUM PLATE

but significantly displaced, core (A_{5m}); the other test series used the creep dominated assembly (B_1) with a close-clearance, near-centerline core (A_1). The data show smaller withdrawal loads when the hoist guide was dis-aligned 0.200 to 0.250 inches in any of the three test directions, than when the hoist was in true alignment. For the displaced core (A_{5m}), the smallest loads were evident when the hoist guide was dis-aligned 0.200 inches and 120° away from free bow. The lateral loads at both receptacle and load pad locations showed minor changes in magnitude for hoist misalignment, but shifted direction for some of the misaligned positions, as would be expected.

Testing of five different configurations of piston rings (corners with .010 max. break, .020 radius, or various bevels) showed similar, and nominal, loads required. Vertical loads were in the 10 to 30 lb. range and lateral loads were in the 1 to 20 lb. range for all configurations tested. Scratching, galling, etc., were negligible. These tests used a straight fuel duct assembly, with grapple misalignment of 0.250" and load pad adjustment of 0.030" to .050" in the opposite direction.

Friction coefficient measurements were performed on a selected combination of metals that were used in the Nozzle Insertion Test Components. These measurements were performed at ambient temperature and at various loadings. The results of these friction measurements, a diagram of the friction test equipment, and the test procedure are in Appendix H.

Inconel 718 components from this testing were also used in another test program to evaluate aluminized diffusion coating of Inconel 718.⁽⁵⁾ Extensive measurement was performed on the Inconel 718 liner from the air-phase tests to provide post-test characterization of this liner. This liner was then annealed, and measured again to provide pre-aluminizing characterization. In addition, 80 small coupons of Inconel 718 were fabricated; 40 of these were aluminized by the vendor of this proprietary process, 39 were age-hardened on-site, and one was retained as fabricated. These coupons were used for irradiation testing of aluminized surfaces. A further item for aluminizing evaluation consisted of simulated piston rings of Inconel 718. These were cut from a partially fabricated liner that was excess as a result of design change.

VI. CONCLUSIONS AND RECOMMENDATIONS

Tests in both air and sodium environments indicate that a chromium-plated nozzle is superior to a bare 316 stainless steel nozzle in minimizing wear damage to FFTF fuel assemblies

without damaging the long life receptacle liner. Loads during initial withdrawal cycles are similar with either nozzle surface; however, with the stainless steel nozzle and repeated insertions and withdrawals, the loads increase.

The type of fuel assembly bowing that is expected from swelling dominated distortion results in the maximum withdrawal and lateral loads. Significantly lower loads were encountered in this testing for the creep dominated bow configuration. It is recommended that design studies and reactor fuel "shuffling" methods be concentrated on counteracting and/or minimizing the accumulation of swelling dominated distortion in the FFTF fuel assemblies. Use of a simulated swelling-dominated fuel assembly as the primary test assembly for future FFTF, LMFBR, or other testing is also recommended.

Load values for fuel assembly movements within a 400° F. sodium environment averaged 1.2 times those measured for the same configuration in an air environment. Primary testing in air environments is, therefore, recommended for configurations of this type, with testing in sodium environments limited to a relatively few verification tests.

The effect of IVHM hoist misalignment (within 0.250 inches) on withdrawal loads is apparently small. It is possible that some reduction in withdrawal loads and, thus, easier fuel assembly withdrawal, may be obtained by slight "jogging" of the IVHM grapple to various positions beside the true centerline. Caution is indicated for this maneuver, however, since excessive disalignment may negate the advantage.

As expected, a close-clearance opening between the fuel assembly and its adjacent neighbors results in maximum withdrawal loads. However, significant displacement of the opening from true centerline does not necessarily result in significant increase in loads, unless the opening is also close-clearance.

VII. ACKNOWLEDGEMENTS

Instrument Engineering support provided by A. E. Mendoza and F. R. Standley contributed significantly to successful load measurement and recording throughout this test program. Prompt scheduling and performance of craft assistance under the direction of C. D. Chapman and J. D. Corder contributed to timely completion of key portions of this testing.

VIII. REFERENCES

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Figure 1

Surface Dose Rate of High Exposure Mixed Oxide Fuel (Lot BLO-34-01-02)

FIGURE 2

Variation Of Neutron Dose Rate With Distance From A Fuel Insert
With 120 FTR Pins

3
Figure 1/- Position of Remab Arm Phantom and Can of Mixed Oxides

5-15

Figure ⁴/₂ Location of TLD's on Arm Phantom

APPENDIX B

The Fuel Assembly Nozzle Insertion Tests described herein involved two of the original nozzle-receptacle designs, a straight cylindrical wall and a stepped wall. The nozzle and receptacle materials were 316 and 304 stainless steel, respectively. Each of the two designs was tested in three different configurations:

1. The nozzle attached to a straight fuel assembly and in alignment with the receptacle.
2. The nozzle attached to a straight fuel assembly, but misaligned a certain amount from the receptacle centerline.
3. The nozzle attached to a bent fuel assembly to represent an FFTF fuel duct after about nine months of irradiation. (Figure B1)

This testing was conducted at ambient temperature and pressure, with pressurized air used to simulate sodium flow in the receptacle. Results from this testing indicate three things:

1. When the fuel assembly is bent, both designs require large forces for either insertion or withdrawal, and the stainless steel nozzle and receptacle surfaces are deeply scratched.
2. Under comparable conditions, the "stepped" cylinder design inserts and withdraws more smoothly and suffers less damage than the straight cylinder.
3. Nozzle-to-receptacle misalignments as great as 0.5 inches, have negligible effect on insertion, withdrawal, or damage, when the fuel assembly is straight.

With the fuel assembly bent, forces, up to 890 lbs. were required to withdraw the straight cylinder design nozzle from the receptacle, and over 1020 lbs. were required for the "stepped" design. Additional force was also needed to insert the nozzles when attached to a bent assembly; maximum insertion forces of over 500 lbs. were needed for both the straight and "stepped" cylinder designs. Scratching and galling to an estimated depth of at least 15 mils, producing many small lumps of metal, occurred on each nozzle, near the tip of the side opposite the bend in the assembly and near the top seal area on the bent side (Figures B2 and B3). Corresponding scratching and galling occurred in the receptacles (Figure B4).

When the assembly was straight and in alignment, no insertion or withdrawal force (beyond the 488 lb. total weight of the assembly and cable, etc.) was required for either the straight or "stepped" cylinder design. Damage was limited to light "scuffing" of nozzle and receptacle surfaces at contact points. Some nozzle rotation was observed during insertion and withdrawal, and the straight

FIG. 8-1

FIGURE B-2. Scratches and galling near tip of nozzle. This side is opposite the bend in the fuel assembly. Neg. 703962-2

FIGURE 8-3. Scratches and galling along nozzle. This is the side on which the fuel assembly bends out. Neg. 703962-1

FIGURE 4. Scratches and galling inside a receptacle after testing with a bent fuel assembly. Neg. 703962-12

cylinder vibrated ("chattered") and bounced up and down during part of each cycle; these actions are attributed primarily to the compressibility and the flow pattern of the air.

With a straight fuel assembly, misalignments as great as 0.5 inch neither increase surface damage nor require any greater insertion or withdrawal forces. Instead, it was noted in this testing that misalignment reduced the tendency for the straight cylinder nozzle design to chatter; until at 0.375 inch or greater misalignment, no chatter was detected.

These results indicate that a movable nozzle joint, or other change in design, is needed to permit satisfactory insertion and withdrawal of bent assemblies. Since major damage occurs near the top of the nozzle, a movable joint, if used, should be located at this point. It appears, from these results, that a joint low on the nozzle would be of little benefit in easing nozzle withdrawal or reducing damage.

Additional nozzle insertion testing was conducted using the bent fuel assembly with various amounts of misalignment. Results show that even minor restraint near the top of the assembly has a major effect on ease of nozzle movement. During initial tests with the bent assembly it was found that the top moved over about 3/4 inch and contacted the upper guide before the nozzle was completely inserted into the receptacle. With the assembly guides in place, a misalignment of only 0.20 inch requires more than 1000 pounds force for insertion of the straight cylinder design after only two insertion-withdrawal cycles (we did not test beyond this point because we had no immediate way to apply more than 1000 pounds force for insertion of the straight cylinder design after only two insertion-withdrawal cycles (we did not test beyond this point because we had no immediate way to apply more than 1000 pounds force on the assembly)). The stepped cylinder design, however, was successfully tested to a misalignment of 0.50 inch, where maximum additional forces required were about 550 pounds for insertion and about 200 pounds for withdrawal.

With the upper assembly guide removed, the straight cylinder was misaligned to 0.25 inch and inserted with a force of about 250 pounds, but at this misalignment the assembly contacted the lower guide. Finally, with the assembly completely freed by removal of both guides, the nozzle (straight cylinder design) was inserted with about 200 pounds force at misalignments of 0.35 and 0.50 inches. The assembly was out of plumb by 1 5/8 and 1 3/4 inches, respectively (measured from the top eye-bolt), when fully inserted at these greater misalignments.

With both guides removed, the top of the fuel assembly moved about quite a bit during insertion and removal, but no significant scratching or galling occurred. Under all other conditions of testing involving a bent assembly the nozzles and receptacles were severely scratched and galled.

APPENDIX C

The articulated design of FFTF fuel assembly nozzle was a first iteration following tests of the straight and stepped cylindrical nozzles (Appendix B). This articulated nozzle (Figure C1) consisted of an upper body, a lower close-clearance nose, and a ring coupling to connect the nose and body while providing limited freedom of movement. The upper body provided slots for coolant flow, an interior chamber for orificing, and an exterior close-clearance region (0.012" annular space, 0.5" long) to control upward flow of sodium outside the fuel duct. This upper body would be welded to the end of the fuel duct. The nose section was attached to the nozzle body with two retaining pins, but was separated from extensive body contact by the ring coupling. This provided for limited universal joint movement of the nose. This 5" long nose section included a 2.75" length close-clearance region (0.012" annular space) to control downward flow of sodium to the plenum below the core support fixture. The tip of the nose included six large open slots; these were designed to mate with corresponding tangs at the bottom of the core support receptacle whenever the fuel assembly is set into place. Except for these 304 stainless steel tangs on the receptacle, the 316 stainless steel nozzle parts contacted only the Inconel 718 surface provided by the liner inside the receptacle.

APPENDIX D

Fuel Assembly Nozzle Tests are described below for the 4-piston ring nozzle with the following test configurations:

- Nozzle (316 SS) with a stepped O.D. and four piston rings to provide ex-core and hydraulic balance flow control; two larger diameter rings were located just above the core coolant slots and two smaller rings were located below these slots and near the lower end of the nozzle (Figure D1).
- Liner (Inconel 718) with two inside diameters to provide appropriate spacing with the 4-piston ring nozzle design. In order to obtain additional information on liner reactions, the liner was supported and constrained by several load cells (four circumferentially and one vertically below the liner) instead of a receptacle; the load cells were positioned to simulate the contact normally provided by the receptacle.
- Simulated fuel assemblies in three configurations, described in Section III B and Appendix E, consisting of straight (B_0), 3-cycle creep (B_1), and 3 cycle swelling (B_2).
- Load cells at top and above-core load pad elevations representing adjacent configurations, as described in Appendix E, consisting of A_1 , A_2 , A_3 , A_4 , and A_5 .
- Adjustable guide on the hoist cable to simulate IVHM grapple misalignment, as described in Section III D and Appendix E.

Results from these tests, summarized in Table D-I, show severe wear and substantial loads for this nozzle design when either creep or swelling distortion of the fuel assembly is simulated. Total forces up to 1200 pounds were required to withdraw a bowed duct assembly under conditions simulating maximum creep (B_1) with the core released 0.050 inches (A_1). Lateral loading on the receptacle liner reached 282 pounds.

Lateral loads at the above-core load pads were 50 to 70 pounds and at the top load pads were 150 to 170 pounds. Significant scratches and galling occurred on the stainless steel nozzle at the "toe" below the lower piston rings, and at the "heel" across the two upper piston rings (Figures D2 and D3). However, the piston rings show no damage.

Total forces up to 2400 lbs. were required to withdraw a bowed fuel assembly under conditions simulating maximum swelling (B_2) with the core released 0.410 inches (A_5). Lateral loadings on the receptacle liner exceeded 700 lbs., and lateral loads at certain above-core load pads exceeded 300 lbs. With the core release restricted to 0.050 inches, this test assembly could not be inserted the final 3 inches with forces up to 1300 lbs. As in tests with the creep simulated assembly (B_1), severe scratches

IN PREPARATION

FIGURE D-1 - FOUR-PISTON-RING
NOZZLE DESIGN

SK-3-16736, Rev. 1 (reduced to $\sim \frac{1}{4}$ size)

TABLE D-I

SUMMARY OF TEST RESULTS
WITH THE 4-PISTON RING NOZZLE AND LOAD CELL SUPPORTED LINER

1. Insertion of straight duct - B_0 :

Maximum insertion force:	400 pounds
Loads generated at ACLP elevation:	20-40 pounds
Loads generated at TLP elevation:	5-20 pounds
Material behavior:	No galling observed, slight burnishing of nozzle

2. Withdrawal of maximum creep/nominal swelling duct - B_1 :

Maximum withdrawal force:	1200 pounds
Loads generated at ACLP elevation:	50-70 pounds
Loads generated at TLP elevation:	150-170 pounds
Material behavior:	Galling of nozzle, transfer of material to liner, top piston rings trapped in grooves.

3. Withdrawal of maximum swelling/nominal creep duct - B_2 :

Maximum withdrawal force:	2400 pounds
Loads generated at ACLP elevation:	250-350 pounds
Loads generated at TLP elevation:	100-300 pounds
Material behavior:	Galling of nozzle, transfer of material to liner, two top and one (upper) bottom rings trapped in grooves.

page D-4

After cycles 1, 2 & 3

After cycle 4

FIGURE D-2

page D-5

After cycles 1, 2 & 3

After cycle 4

FIGURED-3

and galling occurred on the stainless steel nozzle below the lower piston rings, and in the region of the two upper piston rings. Some wear also occurred at the tip of the nozzle discrimination post. Enough metal was "smeared" over the ring grooves to trap the piston rings; forces greater than seven lbs. were required to free the rings. Some scratching occurred on the outer ring surfaces. Examination did not reveal any damage to the Inconel 718 liner. However, the liner retained a significant deposit of stainless steel from the nozzle at both contact points, and this deposit aggravated the galling of fresh nozzle surfaces.

Misalignment of the hoist by 0.200 to 0.250 inch in either the same direction or in the opposite direction from the free bow of the test fuel assembly (i.e., the direction that the top of the bowed assembly is displaced from true center - see Appendix E) showed little additional effect on insertion or withdrawal forces. Maximum vertical force for the creep-simulated assembly (B₁) with this misalignment was 1100 pounds.

Figure 5. HEDL Pure Bend Machine.