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Analysis and Repair of Water-Contaminated Boron Nitride Insulation in BDHT-THTF Bundle 3 Fuel Rod Simulators

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Prepared for the U.S. Nuclear Regulatory Commission
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ACKNOWLEDGMENTS

The entire analysis and repair operation on the Blowdown Heat Transfer—Thermal-Hydraulic Test Facility (BDHT-THTF) bundle 3 fuel rod simulators (FRSs) was conceived and performed under very tight time constraints. This operation was completed within one day of the emergency schedule drawn up a month earlier when the seriousness of the problem was unknown. The completion of this project would not have been possible without the dedication and assistance of many of the BDHT-THTF, Experimental Engineering Section, and Y-12 Craft personnel.

Special recognition is given to John Wolfe and research mechanic John Hackworth for conceiving, fabricating, and installing the new FRS oversleeves; to Ralph Dial and Ken Finnell for their efforts in the analysis, development, and implementation of the many repair procedures and quality assurance inspections vital to this successful effort; and to Herb Martin, Cecil Yearwood, and O. Trull for their expert assistance in inspection and performance of the welding and brazing tasks.

Finally, we wish to acknowledge the initiative and dedication of Glen Mills (now deceased) in perfecting the pressure/off-gas helium leak check technique necessary to guarantee a reliable end plug weld.

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ABSTRACT

The Blowdown Heat Transfer—Thermal-Hydraulic Test Facility bundle 3 fuel rod simulators (FRSs or rods) were installed in June 1979. Three major problems affecting test facility operation were encountered in the following eight months. In March 1980, the rods were removed and transferred to the Engineering Technology Division FRS Technology Development Laboratory. Electrical inspections and fault isolation checks revealed that water had contaminated the annular boron nitride insulation in the region of the O-ring seals near the power supply or upper terminal end of the units. The extent of the damage was determined, a repair process was developed and implemented, and 87% of the FRSs were repaired and returned to service. Extra FRSs were prepared as substitutes for the permanently damaged rods.

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1. INTRODUCTION

Fuel rod simulators (FRSs or rods) for the Blowdown Heat Transfer—Thermal-Hydraulic Test Facility (BDHT-THTF) were fabricated in the Engineering Technology Division FRS Technology Development Laboratory (TDL) and installed in the THTF in June 1979. Reference 1 details their development and fabrication. The FRSs are very sophisticated electric heaters that simulate light water reactor fuel rods in geometry and thermal characteristics for out-of-reactor thermal-hydraulic experiments.

Table 1 summarizes the operational history of THTF bundle 3 after the FRSs were installed. Nonpowered tests were conducted early in November 1979; later that month the first power was applied to the rods. This early testing was plagued by unexplained functioning of electrical fault-detection devices (crowbars), which remove voltage from each FRS if an overcurrent condition develops. Bundle uncovery/recovery tests, in which the water level in the powered bundle is gradually reduced, were conducted in December 1979 and January 1980. After these tests, some water leakage was discovered in the region of the lower set of elastomer O-rings sealing the upper or terminal end of the rods (Fig. 1) into the pressurized-water system. Single-rod full-power (120-kW) tests were conducted in February 1980. Four of the 60 FRSs were unable to reach full power without a fault condition (crowbar) occurring. That same month, a second bundle uncovery test was conducted; during this time, massive terminal leakage occurred.

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*Development Division at Y-12.

Table 1. BDHT-THTF FRS operational summary

Operation	Date	Remarks
Rods installed	6/79	
Water circulated	8/79	
Isothermal blowdown	11/79	
Power to rods	11/79	Unexplained activation of crowbars[a]
Low-power testing	11/79 to 2/80	Unexplained activation of crowbars
Bundle uncovery/recovery tests	12/79 to 1/80	Lower O-ring leakage
80 kW per rod	2/80	Crowbars; some terminal leakage
Single-rod power tests	2/80	Four rods unable to reach full power
Bundle calibration test	2/80	Massive terminal leakage
Testing discontinued	2/80	Terminal arcing discovered
Rods removed	3/80	
Rods repaired and replaced	4/80	
Testing resumed	5/1/80	Rods O.K.
90 kW per rod	5/2/80	Rods O.K.
120 kW per rod	5/15/80	Rods O.K.
First blowdown		Premature power cutoff
120 kW per rod	5/21/80	
Second blowdown		

[a]Electrical fault isolation devices.

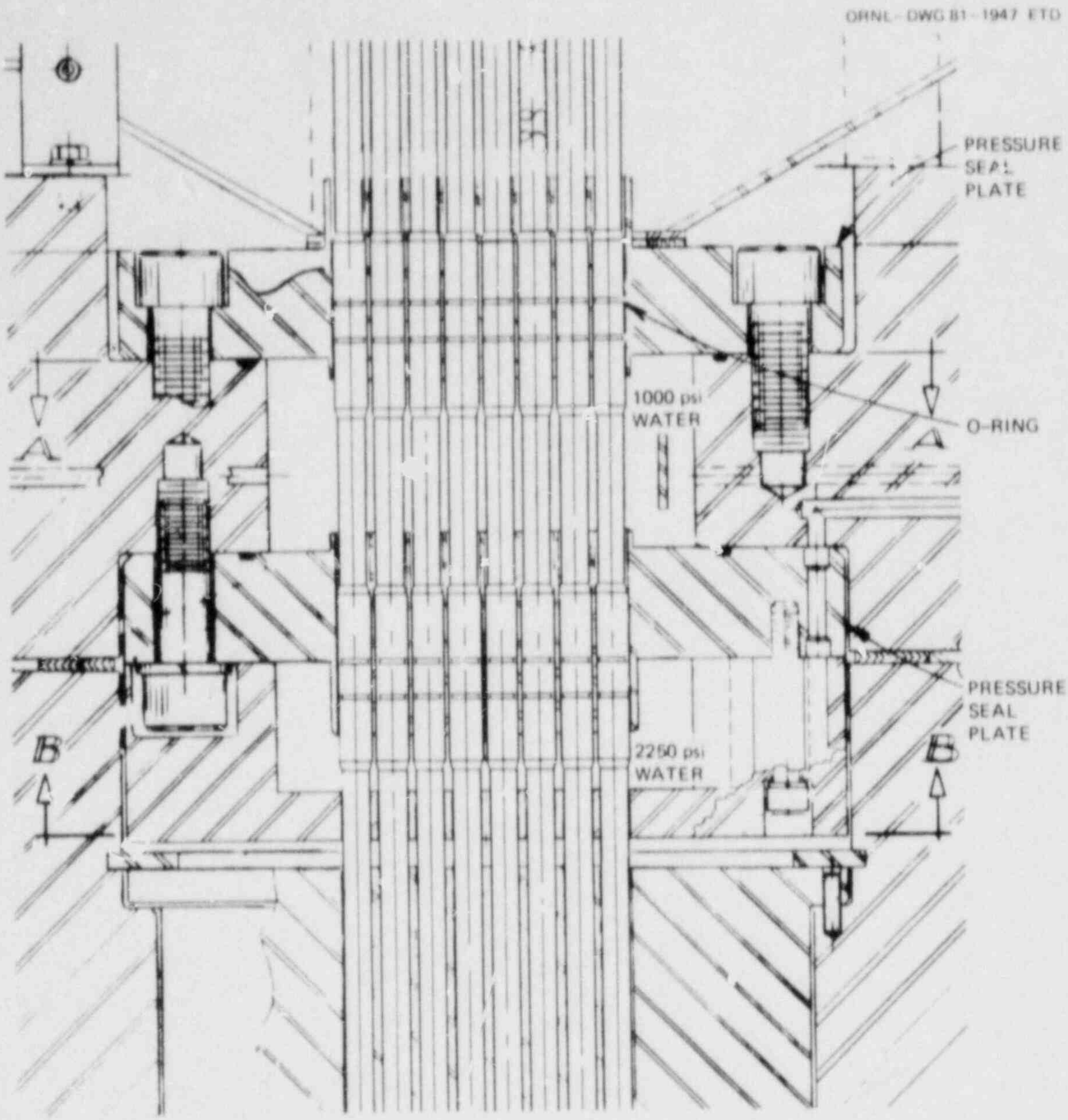

Fig. 1. Upper test section of THTF bundle 3.

Testing in the THTF was discontinued in February 1980, and the rods were removed for examination in March. At this time, the third major problem (the first ones being crowbars and terminal leakage) was discovered; severe arcing had occurred between the FRS terminals in the power connection region (Fig. 2).

Initial visual examinations of the FRSs indicated that some had been overheated in the O-ring seal region. Several FRSs exhibited local swelling of the clad and had severely burned O-rings.

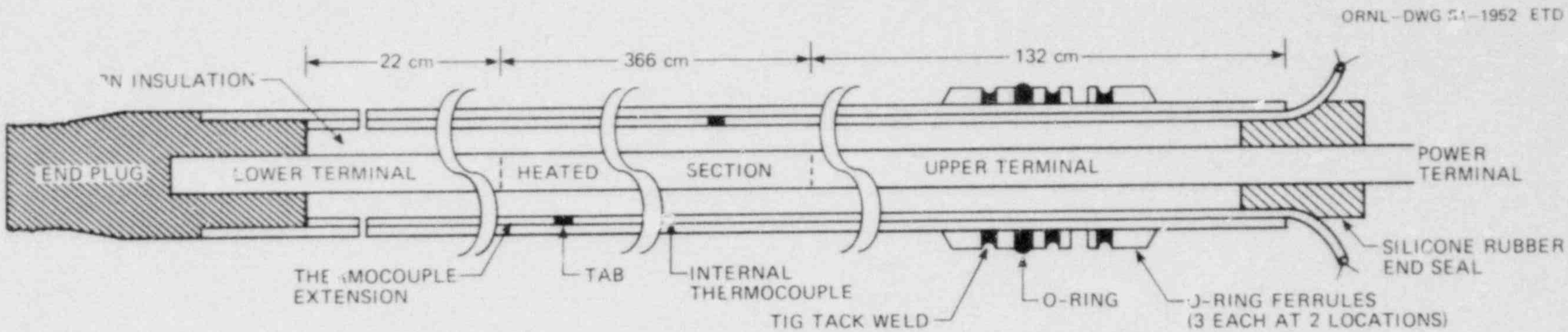

Fig. 2. BDHT-THTF bundle 3 FRS.

Because the FRSs had incurred some damage, they were transferred to the FRS TDL for further investigation of the short-circuiting and leakage problems. Meanwhile, investigation of the terminal arcing problem revealed flaws in the FRS crowbar circuits, which apparently had caused voltage feedback and interference. The arcing was further enhanced by the presence of water in the terminal region caused by the leaking O-rings. The terminal spacing was ~3 mm (0.118 in.), with uninsulated terminal lengths up to 125 cm (49 in.) separated by Micarta standoffs. Differential expansion and bowing during operation caused terminal-to-terminal spacing to decrease. This spacing decrease and feedback during rod crowbars caused high transient voltages, resulting in sporadic arcing. Crowbar circuit improvements and terminal insulation would effectively correct these problems. However, the problem of FRS damage, which caused short-circuiting and system leakage, was more elusive.

2. ANALYSIS AND RESULTS

2.1 General

Figure 1 shows the upper portion of the test section of THTF bundle 3. The FRSs are rigidly bolted to a nickel plate (not shown) at the bottom of the test section. Thermal expansion is accommodated at the pressure seal plates by the four O-rings. The lower pair of O-rings sustain a maximum pressure drop of 8.62 MPa (1250 psi) from 15.51 MPa (2250 psi) in the bundle region to 6.90 MPa (1000 psi) in an intermediate-pressure water coolant circuit. The upper O-rings isolate the 6.90 MPa (1000 psi) pressure in the water-cooled section from ambient conditions. The maximum temperature in the O-ring region is ~177°C (350°F).

Figure 2 is a simplified diagram of the BDHT-THTF FRS. The heating element consists of a 132-cm (52-in.) upper terminal section, a 366-cm (144-in.) heated section, a 22-cm (8.7-in.) lower terminal, and an end plug, which grounds the lower terminal to the stainless steel clad. The heating element internal volume and FRS annular region are insulated with boron nitride (BN). The annular region contains 12 thermocouples (TCs) that extend the entire length of the FRS and are in contact with the inner diameter (ID) of the stainless steel clad. All clad TCs have BN-backfilled insulated junctions, followed by a short (3-mm) solid metal tab of the same diameter as the TCs and a "dead" length of sacrificial thermocouple material, which extends to the end plug. Details of one of the O-ring ferrule sets are shown. Each set of O-rings is held by three ferrules. Each ferrule is tacked to the stainless steel sheath in four places by a tungsten-inert gas (TIG) weld. The O-rings are positioned between the ferrules and contact both the rod surface and the IDs of holes through the pressure seal plates.

From the initial visual inspections, several of the rods apparently were damaged in the O-ring seal region. The critical questions were (1) how many rods were damaged, (2) what caused the problems, and (3) could the damaged rods be repaired?

2.2 FRS Examinations

The answer to the first question depends on the value of the annular insulation resistance (IR). The original criterion for bundle 3 FRS was that this resistance was $>10^9$ Ω at room temperature. To obtain IR measurements, it was necessary to isolate the FRS clad from the heating element by cutting a 1.5-mm-wide (0.060-in.) circumferential groove through the sheath and BN in the 22-cm (8.7-in.) lower terminal region just above the end plug (Fig. 2). A process was then developed, tested, and verified for resealing the region by (1) beveling the sheath on both sides of the slit, (2) cleaning BN from the region, (3) inserting a 2.25-mm-diam (0.088-in.) Inconel 600 weld wire, (4) swaging the weld wire in place to seal BN from the weld area on both sides of the cut, (5) cleaning the affected region, (6) TIG welding it closed, and (7) performing dye and helium leak checks on the closure to ensure its integrity.

A standard helium leak check could not be performed because the weld was essentially a surface weld that closed off the rod internals. A pressurize/monitor helium check system was devised to circumvent this problem. The region was enclosed in a "T" with O-ring seals on both sides of the weld region and was pressurized for 30 min at 1.38 MPa (200 psi). The T was then removed and the region was cleaned with ethyl alcohol. A second T was then installed and connected to the helium leak check device. The rate of helium off-gassing was then monoitored. A good standard showed an initial leak rate of $\sim 2.6 \times 10^{-8}$ cm^3/s (1.6×10^{-9} in.^{3}/s), which was decreased to less than 1.0×10^{-8} cm^3/s (6.1×10^{-10} in.^{3}/s) in 30 min. A defective weld registered 10 to 100 times that leak rate and, thus, was immediately detectable.

After the development of a successful closure process, the FRS sheaths were cut, and insulation checks were performed. The standard checks are (1) a 500-V IR check, (2) a 1500-V high-potential check, and (3) a repeat of the IR check. The acceptance criterion was a maximum of 0.5 mA current leakage across the insulation gap in step 2 with measured resistances of $>10^9$ Ω in steps 1 and 3.

Table 2 summarizes these tests and compares them with the orignial IR checks made on all rods before they were turned over to the BDHT program. Most FRSs had experienced a drop in IR; 60% were below the acceptance criterion and considered damaged, while 35% measured $<10^3$ Ω and were thus considered severely damaged.

Table 2. Results of annular IR checks on FRSs removed from THTF bundle 3

IR	Number of rods	
	Originally	After removal
$>10^{12}$ Ω	8	2
$>10^9$ Ω	52	22
$>10^{6a}$ Ω	0	7
$>10^{3a}$ Ω	0	8
$<10^{3a}$ Ω	0	21
Total	60	60

[a] Sixty percent of the rods were in these "damaged" categories.

2.3 FRS Fault Isolation Checks

To better determine the extent of damage and to learn what caused the problem, powered fault isolation checks were performed on those rods that had an IR $<10^3$ Ω. These checks consisted of connecting a variable voltage power source across the insulation and monitoring the current leakage. Regions that were low in IR permitted current flow and local heating. The local power generated was controlled by the relationship of voltage to resistance; as resistance decreased, power increased proportionally. Resistance in the severely damaged rods ranged from 40 to ~800 Ω.

Those regions of the rods with low resistance were also unstable in resistance as evidenced by the variability of the current readout. Many rods began to show a greater decrease in resistance as they were heated. All severely damaged rods exhibited heating in the oversleeve region adjacent to one or more sets of ferrule welds. Steam/water and BN spewed from some rods as they were heated. At this point, it became evident that many of the TIG tack welds had punctured the sheath, exposing the annular BN to water.

Examination of the BN, as well as discussions with BDHT program staff, Y-12 craft personnel, and inspectors led to these observations:

1. The TIG tack weld was difficult to do properly. In retrospect, some other attachment procedure, which had a greater chance of success, might have been developed.
2. Although a welder and the weld process were qualified on samples prior to Bundle 3 FRS ferrule welding, other unqualified welders were later used to perform most of the welding.
3. An acceptable helium leak check method was not available, and dye checks were inadequate to show defects because of the ferrule geometry; therefore, only visual checks for weld quality were made.
4. No formal weld inspection was specified.

In retrospect, it is obvious that the program staff was under tremendous pressure to complete the bundle installation. Therefore, some operations were performed on a "crash" basis without inspection, contrary to standard procedures.

2.4 FRS Fault Analysis and Repair Operations

To determine if the damaged rods were reparable, several parallel investigations were conducted:

1. a literature search of $BN-H_2O$ reactions,
2. infrared scans of several faulty regions,
3. micrographs of sections through several defective regions,
4. an ion microprobe scan of the surface of a section from a defective region,
5. X-ray fluorescence and X-ray diffraction examination of a defective region, and
6. development of methods for removing water from the FRSs.

2.4.1 $BN-H_2O$ reactions

Because water certainly had come in contact with the annular BN, it was necessary to assess the extent of the $BN-H_2O$ reactions under the assumed temperature-pressure-time conditions. These conditions were ~200°C (392°F) and 15.51 MPa (2250 psi) for a few hours at most. Under low- or no-power conditions, the temperature would have been less, probably <100°C (212°F). Conversely, once the electrical resistivity in the rod insulation decreased, local I^2R heating would eventually result in temperatures >200°C (392°F). As the temperature increased, local BN resistivity decreased, futher increasing I^2R heating and, thus, temperature.

Reaction products of BN and H_2O include boric oxide (B_2O_3), boric acid (H_3BO_3), and ammonia (NH_3).[2] These products can be obtained through one of the following reactions:

$$2BN + 3H_2O \rightarrow B_2O_3 + 2NH_3 \quad (1)$$

$$BN + 3H_2O \rightarrow H_3BO_3 + NH_3 \quad (2)$$

$$B_2O_3 + 3H_2O \rightarrow 2H_3BO_3 \quad (3)$$

Each of these reactions occurs when H_2O is combined with powdered BN at moderate temperatures. The probability of these reactions was supported by the smell of ammonia when a cut was made through the clad of one FRS. Whether the reaction products would cause permanently harmful effects was still not clear.

The BN in the annular region of the completed FRS is at 97% of its theoretical density. For a chemical reaction to take place, the two reactants must come into contact. With only 3% porosity, the contact area would normally be restricted to the outside surface of the BN, but at 15.51 MPa (2250 psi), some possibility exists that the water would penetrate the annular BN volume. All these reaction products are very water-soluble, which could increase the reaction rate by removing reaction products and uncovering unreacted BN. The dissolution of reaction products should also increase annular electrical conductivity.

An increase in electrical conductivity does not necessarily indicate extensive $BN-H_2O$ reactions, however. Boron nitride is a very hygroscopic material, and absorbed water would also cause the high conductivity shown by the FRSs. Evidence that tends to support limited reactivity includes: (1) studies on BN fibers that show little reaction for the times and temperatures postulated (Fig. 3 and Table 3) and (2) IR readings that showed the same type of instability under voltage stress that had previously been attributed to absorbed water. Because of its very high density, the behavior of BN in the sheath should be similar to the behavior of BN fibers, thus enhancing the probability that the $BN-H_2O$ reaction might have been negligible.

The reaction products (a basic acid and a basic oxide), when dry, are also electrical insulators at temperatures up to ~500°C (932°F). Because the maximum temperature of the O-rings and the oversleeve area is limited to ~200°C (392°F), these contaminants should have no effect on FRS operation.

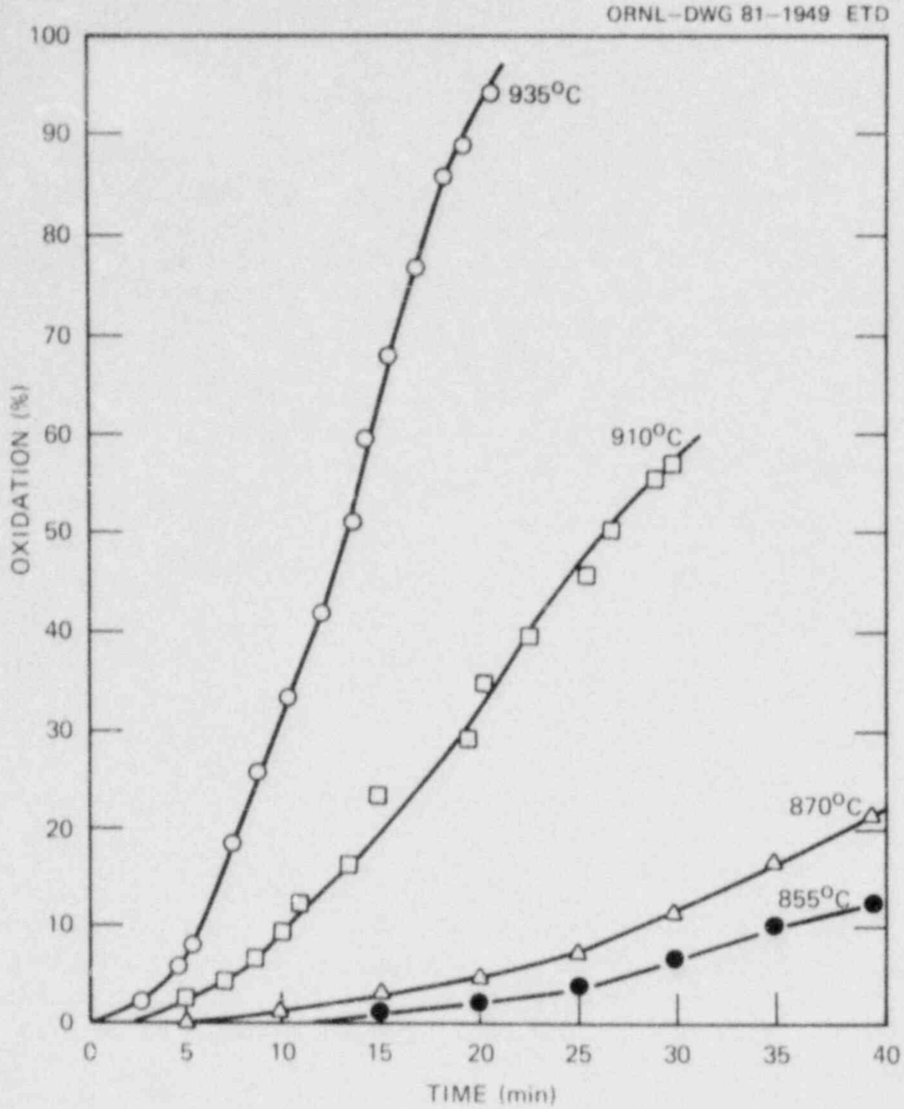

Fig. 3. Isothermal oxidation of BN fibers. (From Ref. 2)

Table 3. Resistance of BN fibers to water (from Ref. 2)

Reagent	Temperature (°C)	Time	Weight loss (%)
H_2O	25	2 weeks	0.0
	25	8 weeks	0.0
	100	75 h	0.1
Steam	600	1 h	0.0
	700	1 h	0.8
	775	1 h	5.0

Thus, BN-H_2O reactions had occurred but were probably not extensive, most of the reaction products could be removed (or made inactive) by removing the water, and any dry boric acid (H_3BO_3) and boric oxide (B_2O_3) remaining would not alone reduce the electrical IR at normal use temperatures of 177°C (350°F) and below.

2.4.2 Infrared scanning analysis

Figure 4 summarizes the results of a transient infrared scan of an FRS with defective ferrule welds. The four scans show the local axial clad temperature in 90° quadrants in response to a voltage impressed across the affected insulation. The IR of this specimen was ~200 Ω. The 180° orientation plot shows the circumferential location at which the insulation defect is most pronounced. More importantly though, these scans show that the defect is axially very localized with a total affected region ~7 cm (2.8 in.) in length and a peak hot spot ~1 cm (2.5 in.) in length.

2.4.3 Micrographs and metallurgical analysis

A severely damaged FRS for which the local defects had been isolated by infrared scanning was sectioned and photomicrographed. Figure 5 shows micrographs (a) close to and (b) at the affected area. A dark region is evident around the Inconel 600 heating element, cracks are visible in the annular BN, and stringers appear to run from the heating element to the annular thermocouples. The BN in the hot spot region is very dark and has a low resistance, whereas the BN only a few millimeters away is more normal.

Ion microprobe analysis of the region in (b) revealed 1.7% Ni present in the BN. X-ray florescence and X-ray diffraction showed the dark area to be nickel borate $Ni_3B_2O_6$.

Although some conflicting evidence from X-ray analysis exists, it seems plausible that borates were formed in the rods that got very hot, permanently decreasing the IR. As the insulation became saturated with water, the resistance was lowered causing more local heat generation. This resistance decrease caused the temperature in the affected region to increase drastically, probably to 1000°C or more. At these temperatures, the nickel borate formation, as well as the other three reactions, took place rapidly. Above 600°C (1112°F), B_2O_3 becomes a liquid and probably assists in the borate reactions.

In rods that got hot enough to undergo these reactions to any extent, damage would be irreversible.

2.4.4 FRS dehydration

The BN IR is extremely sensitive to contamination, and its measurement is very simple to perform. Thus, IR checks were absolutely indispensable as an analytical tool for monitoring dehydration and as a quality assurance (QA) tool in eventual FRS repair.

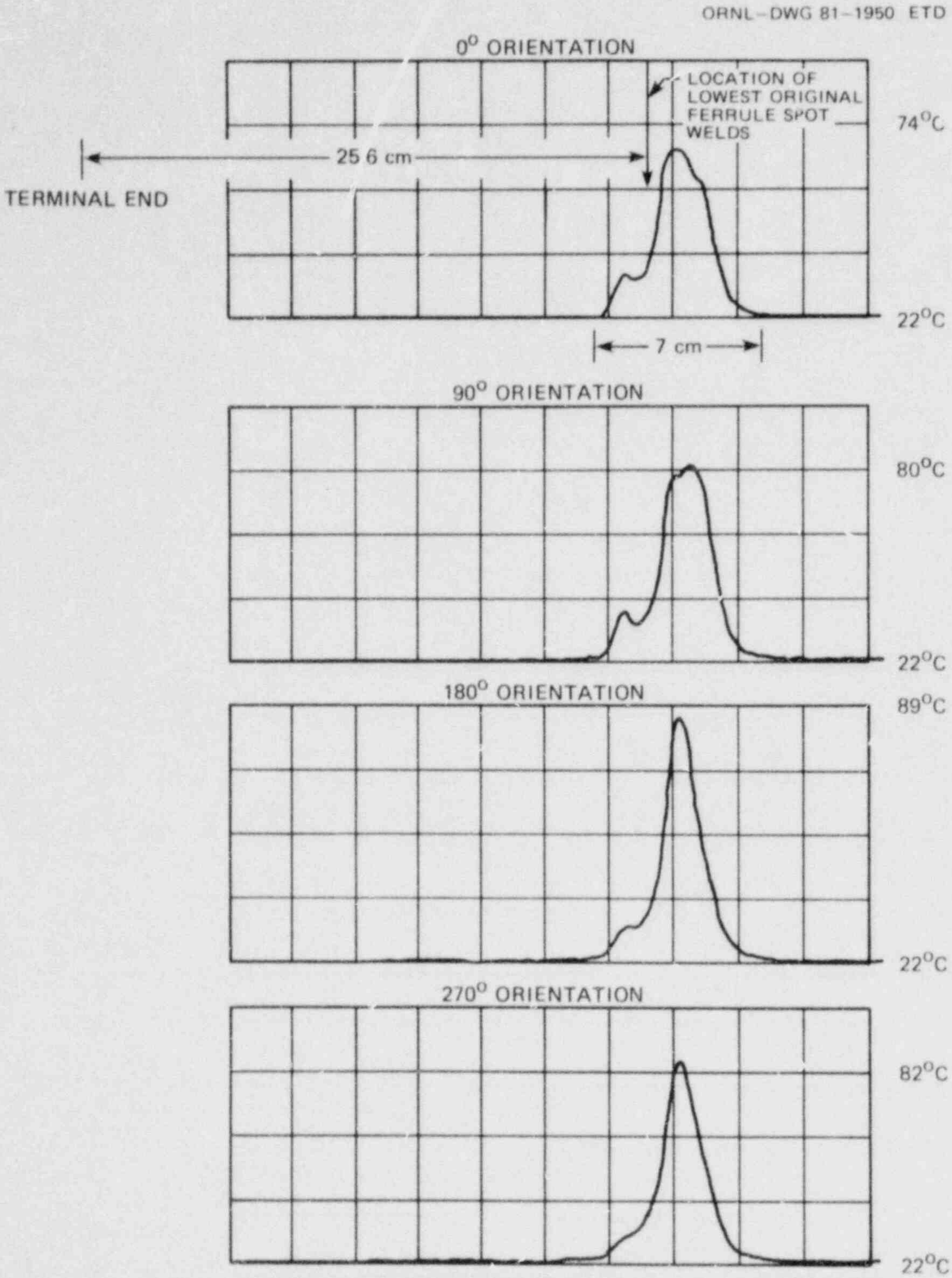

Fig. 4. Infrared scans used to precisely locate rod defects.

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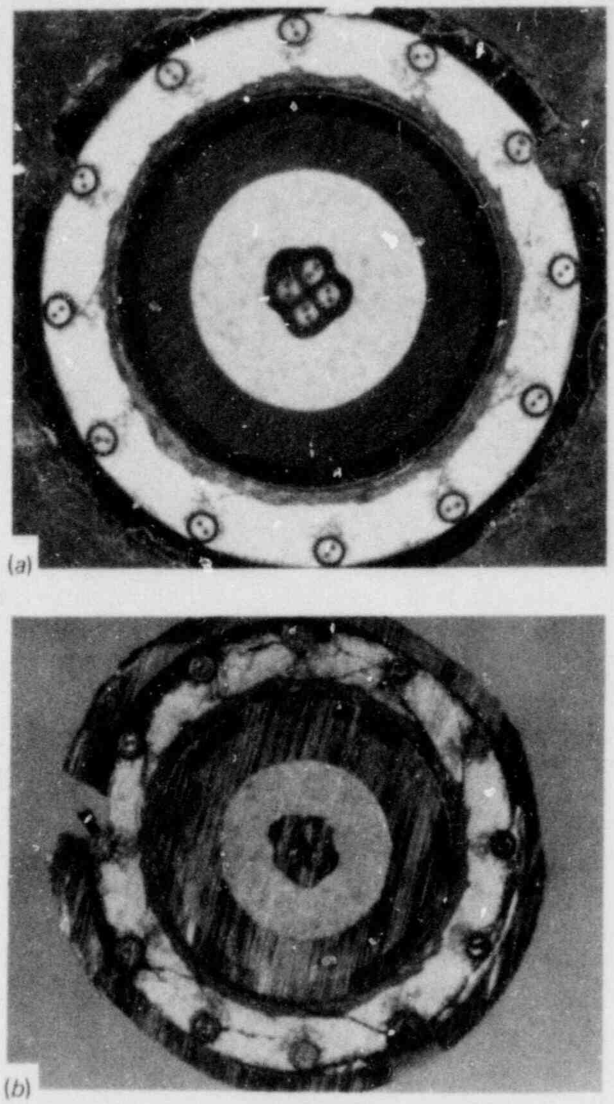

Fig. 5. Micrographs of defective region of FRS. (*a*) Cross section of FRS 2.5 mm from peak in infrared scan, 10×; (*b*) cross section of FRS at peak in infrared scan, 10×.

From the preceeding analysis, it was reasoned that, if water was removed, all rods except those which underwent borate reactions would show an increase in IR because B_2O_3 and H_3BO_3 (dry) are insulators. If the oversleeve region is maintained below 177°C (350°F), a condition necessary for the survival of the O-rings, the IR would remain high.

The FRSs were dried and IR checks were made to monitor the extent of water removal by performing the following additional operations:

1. stripping off the ferrules on all rods and drilling several 0.75-mm (0.030-in.) holes in the ferrule weld region (if the FRS was $<10^9$ Ω);

2. baking out most FRSs with IR <10^9 Ω at 250°C (482°F), 20-μ vacuum for 4 to 7 d; and
3. using the infrared-scanning power supply to locally heat rod sheaths to 300°C (572°F) for 1 to 10 d.

These actions returned ~75% of the FRSs to their original IR state. For those rods still low in IR, the following additional operations were performed:

1. the affected region was locally heated with a propane torch,
2. a welder locally heated the affected region with an oxy-acetylene torch to ~900°C (~1652°F), and
3. the upper 2 to 5 cm (1 to 2 in.) of cladding was stripped from several FRSs that still contained localized shorts in this region.

Table 4 summarizes the results of this thermal repair operation. Seven of the 21 rods with IR <10^3 Ω were not reparable, while only one of the remaining 39 rods with an IR >10^3 Ω was not reparable. Extra FRS, fabricated earlier, were substituted for defective rods.

Table 4. Summary of BDHT FRS thermal recovery

Initial IR range	Number of rods	Number of rods recovered	Final IR			
			MΩ range	0–500GΩ range	500G-ITΩ range	>ITΩ
<lKΩ	21	14		6		8
KΩ	8	7		3[a]	2	2
MΩ	7	7	1[b]	4		2
GΩ	22	22		16	5	1
TΩ	2	2		2		
Totals	60	52	1	31	7	13

[a]Rod 51 has a consistent 9 μA at 1500-V leakage from the start of the recovery to the final stage. This rod was accepted on the basis of its stability.

[b]Rod 9 had an initial IR of 1.5 MΩ and a 3500 μA leakage at 1500 V. The final IR was 150 MΩ with a 13 μA leakage. This rod was accepted on the basis of the improvement and because the electrical parameters were stable.

3. FRS REPAIR

Many, if not all, of the FRSs that responded to the dehydration process contained weld cracks and/or drilled holes in the clad in the ferrule region. A repair method that would not allow water to again reach the BN in this region had to be devised. It was also necessary to devise an absolute QA process that allowed no defective FRSs to be accepted inadvertently (Fig. 6).

The former problem was solved by the design and fabrication of an oversleeve that slipped over the entire ferrule region and had grooves machined in its surface to accommodate the O-rings (Fig. 7). The very small clearance between its ID and the FRS clad made it difficult to install. However, the sleeve effectively covered the defective region, was mechanically sound, was brazable to the FRS clad, and was easily inspected after both its fabrication and installation.

An additional, and unanticipated, advantage of this oversleeve was realized when the THTF pressure seal plate was examined. The rod penetration holes on the seal plate had been chrome plated to provide a smooth surface to accommodate movement of the O-rings during rod thermal expansion. The chrome plating had not adhered properly or had been damaged by high temperatures. Oversleeves used to repair the rods increased the O-ring OD sufficiently to permit salvaging the damaged seal plate. The seal plate holes were reamed to a larger size to remove all traces of chrome plating and successful sealing was achieved without the use of plating.

An Ag-Cu-Ni braze material with a melting point of 927°C (1700°F) was selected as the optimum braze material because conventional silver solder Ag-Cu (although more easily brazed) was reported to be susceptible to erosion when in contact with high-temperature water.[3] The braze material was used with a flux which was easily cleaned from the surface in contact with water; the braze was inspected by standard dye and helium leak checks. Additionally, X-ray checks were made to ensure adequate braze penetration. Finally, electrical checks of the BN insulation were made after the braze operation to ensure that the BN was not recontaminated through the clad holes.

The upper braze [terminal end (Fig. 7)] on the oversleeve was similar to the lower braze (and facing the heated section) but, because the upper braze would not be exposed to water, no helium leak check was used. Electrical inspections were performed after each critical operation.

Complete inspection of all FRSs was maintained throughout all operations by electrical, dye, and helium leak checks. All braze and weld processes were qualified prior to use, each welder was certified by an inspector, and an inspector was present during all welding and brazing operations. Throughout the process, QA information was obtained on all rods (Fig. 6).

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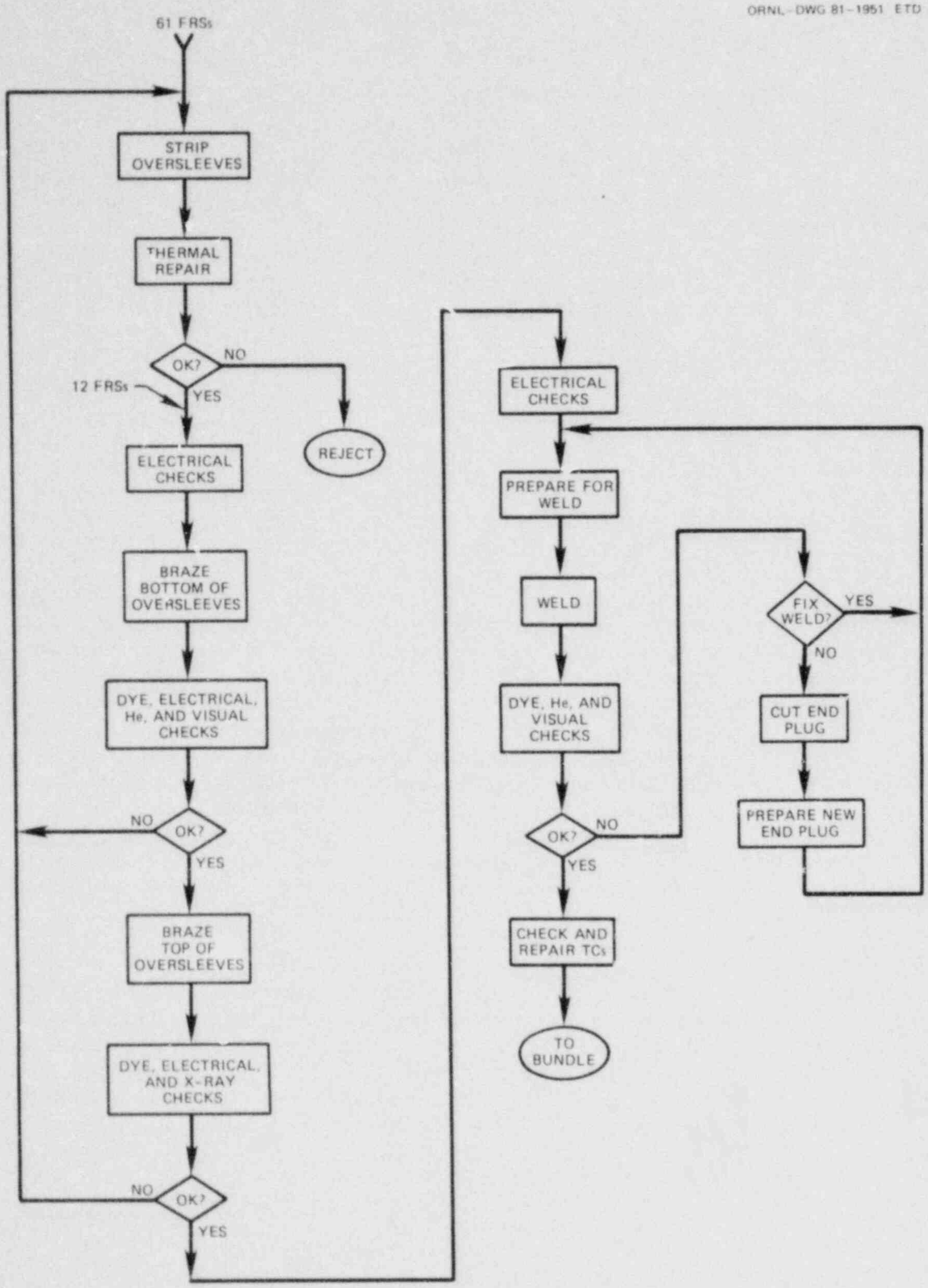

Fig. 6. BDHT-THTF FRS repair flow chart.

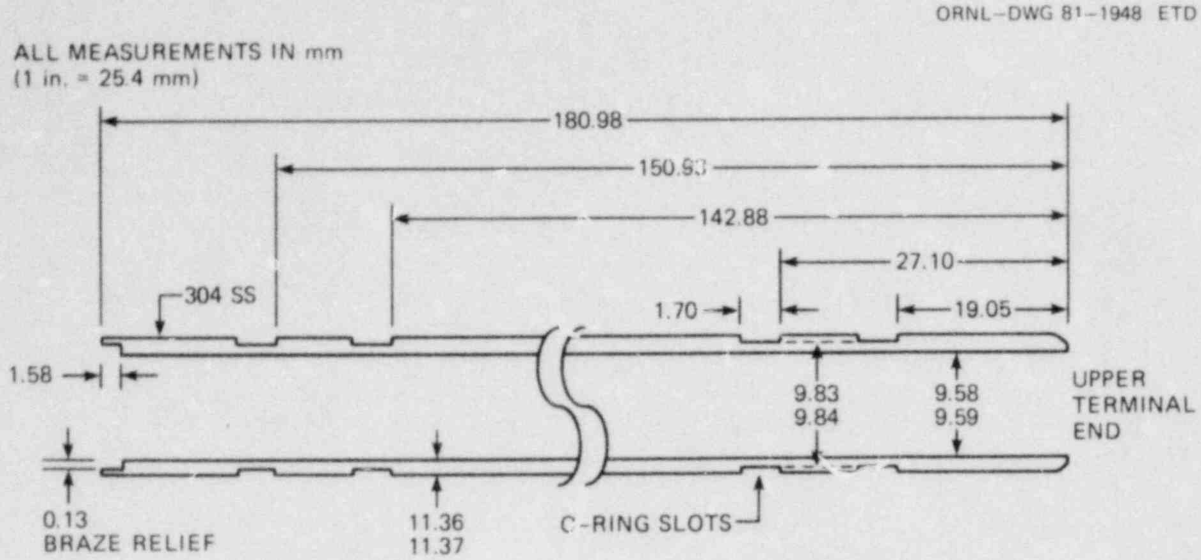

Fig. 7. FRS oversleeve.

4. SUMMARY

Operational problems with THTF bundle 3 over several months finally resulted in the removal of bundle FRSs from the facility. Investigations revealed that O-ring ferrule welds, which attach the ferrules to the FRS sheath, had been faulty. Water, aided by thermal expansion, temperature, and loop pressure, had penetrated the annular BN insulation in the O-ring region of most FRSs.

Using FRS annular IR (which is extremely sensitive to BN contamination) as the primary fault indicator, techniques were developed to isolate the fault, determine the extent of damage, and finally to dehydrate the FRSs. Fifty-two of sixty FRSs were successfully dehydrated and eight permanently damaged FRSs were replaced with spares.

A new oversleeve was designed and fabricated, a process for decoupling and recoupling the end plug (to enable BN insulation checks) was developed, and a repair process enabling complete FRS refurbishment was devised. A safe braze process that could be inspected was used; helium leak, dye penetrant, and electrical checks were incorporated to assure totally reliable FRS repair.

The repaired FRSs were reassembled into the THTF, and successful operation was conducted. A total of 18 h of powered operation, including three power drops, an upflow film boiling test, and a blowdown, was logged. During this time, the FRS Technology Development Group fabricated ten additional FRSs, incorporating twelve 0.38-mm (0.015-in.) BN-backfilled clad thermocouples in each rod. These thermocouples contained junctions at axial locations, which provided the capability to perform investigations supporting the Three Mile Island (TMI) Nuclear Plant accident. After the substitution of these rods for previously placed spares, an additional 58 h of powered operation was logged. This operation included two blowdowns, one power drop, and 70 bundle uncovery/recovery tests in direct support of TMI. Most powered operations, including 16 of the 70 bundle uncovery tests, were at 100 to 127 kW per rod. The maximum clad temperature recorded was 760°C (1400°F). No oversleeve failures or unanticipated O-ring failures occurred.

The bundle is currently fully operational and available for future out-of-reactor investigations.

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