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DOE RESEARCH AND
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OUT-OF-PILE HYDRIDING AND THERMAL
RELAXATION OF REACTOR FASTENERS USING
ZIRCALOY COMPONENTS - THE REM-120 TEST
(LWBR Development Program)

JANUARY 1980

CONTRACT DE-AC11-76PN00014

BETTIS ATOMIC POWER LABORATORY
WEST MIFFLIN, PENNSYLVANIA
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OUT-OF-PILE HYDRIDING AND THERMAL RELAXATION OF REACTOR FASTENERS
USING ZIRCALOY COMPONENTS - THE REM-120 TEST

(LWBR Development Program)

D.A. Duenkel

Contract DE-AC11-76-PN00014

January 1980

Printed in the United States of America
Available from the
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151

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FOREWORD

The Shippingport Atomic Power Station located in Shippingport, Pennsylvania was the first large-scale, central-station nuclear power plant in the United States and the first plant of such size in the world operated solely to produce electric power. This program was started in 1953 to confirm the practical application of nuclear power for large-scale electric power generation. It has provided much of the technology being used for design and operation of the commercial, central-station nuclear power plants now in use.

Subsequent to development and successful operation of the Pressurized Water Reactor in the Department of Energy (DOE) owned reactor plant at the Shippingport Atomic Power Station, the Atomic Energy Commission in 1965 undertook a research and development program to design and build a Light Water Breeder Reactor core for operation in the Shippingport Station.

The objective of the Light Water Breeder Reactor (LWBR) program has been to develop a technology that would significantly improve the utilization of the nation's nuclear fuel resources employing the well-established water reactor technology. To achieve this objective, work has been directed toward analysis, design, component tests, and fabrication of a water-cooled, thorium oxide-uranium oxide fuel cycle breeder reactor for installation and operation at the Shippingport Station. The LWBR core started operation in the Shippingport Station in the Fall of 1977 and is expected to be operated for about 4 to 5 years. At the end of this period, the core will be removed and the spent fuel shipped to the Naval Reactors Expended Core Facility for a detailed examination to verify core performance including an evaluation of breeding characteristics.

In 1976, with fabrication of the Shippingport LWBR core nearing completion, the Energy Research and Development Administration, now DOE, established the Advanced Water Breeder Applications (AWBA) program to develop and disseminate technical information which would assist U.S. industry in evaluating the LWBR concept for commercial-scale applications. The program is exploring some of the problems that would be faced by industry in adapting technology confirmed in the LWBR program. Information being developed includes concepts for commercial-scale prebreeder cores which would produce uranium-233 for light water breeder cores while producing electric power, improvements for breeder cores based on the technology developed to fabricate and operate the Shippingport LWBR core, and other information and technology to aid in evaluating commercial-scale application of the LWBR concept.

All three development programs (Pressurized Water Reactor, Light Water Breeder Reactor, and Advanced Water Breeder Applications) are under the technical direction of the Division of Naval Reactors of DOE. They have the goal of developing practical improvements in the utilization of nuclear fuel resources for generation of electrical energy using water-cooled nuclear reactors.

Technical information developed under the Shippingport, LWBR, and AWBA programs has been and will continue to be published in technical memoranda, one of which is this present report.

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Six different fastened joints representing the various combinations of materials in contact with Zircaloy in the Light Water Breeder Reactor (LWBR) were tested in 520°F water for 60 days to determine the out-of-pile hydriding tendencies of the Zircaloy components in the joints. No evidence of massive, accelerated hydriding was found in this test although other testing reported in Reference (1) has shown that local hydriding can occur in one of the fasteners. The same six fastener designs were tested in 600°F water for 60 days to assess their load retention capability (thermal relaxation). The measured relaxation of these fasteners confirmed the predicted values for the conditions of the test.

OUT-OF-PILE HYDRIDING AND THERMAL RELAXATION OF REACTOR
FASTENERS USING ZIRCALOY COMPONENTS - THE REM-120 TEST
(LWBR Development Program)

D.A. Duenkel

I. INTRODUCTION

The REM-120 test was one of a series of LWBR Reactor Engineering Mechanical (REM) tests and was performed to provide data concerning the hydriding and the load retention (relaxation) performance of typical fastened joints used in the Light Water Breeder Reactor (LWBR). The hydriding portion of the testing was performed to evaluate the out-of-pile hydriding tendencies of Zircaloy-4 components in contact with other materials in various fastened joint designs. The results of additional testing of the hydriding of Zircaloy when in contact with nickel were reported in Reference (1). The load retention testing was performed to demonstrate that the thermally induced relaxation of the fastened joint behaved as predicted.

Six different fastened joint designs were tested in both the hydriding and the relaxation phases. These designs are typical of in-core structural connections including grid, shell, and fuel rod fastened joints which are discussed in Reference (2), Core Mechanical Design Section. These six were chosen to represent the range of size and materials used in LWBR and provided technology supporting the LWBR design. Figure 1 through 6 illustrate each of the fastened joint designs tested with the materials in the joint indicated.

In particular, the seed rod to baseplate joint, as shown in Figure 6, was tested since the Zircaloy rod end connector and the nut were tightened into the plastic range to provide sufficient end-of-life load in the connection.

II. HYDRIDING TEST

A. Test Specimen Description

The REM-120 specimens used for the hydriding test are listed in Table I with the material listed for each of the components. Table I lists the materials in the order of the male threaded component first, the clamped component(s) second and the female threaded component last. The thread size for each type of joint is listed in Table III. As indicated in Table I, some of the hydride test specimens were soaked in a potassium tetraborate solution (PTB) prior to their test exposure. The estimated hydride concentrations in the specimens for pre- and post-test are given.

1. Seed-Grid to Post

The seed-grid to post specimen (Figure 1) consisted of an AM-350 (a type of age hardenable stainless steel) bolt (#10-32) which clamped an AM-350 lug and a Zircaloy-4 ledge with a 304 stainless steel nut. The AM-350 lug simulated a mounting lug on a fuel rod support grid. A 304 stainless steel locking tab rested between the Zircaloy ledge of the post and the AM-350 lug. The locking tab was included to retain the bolt in place if the bolt failed in service. The 304 stainless steel nut had a sleeve extending beyond the threads which was crimped onto a concentric sleeve extension of the bolt. This crimp locked the bolt preventing rotation. This connection is also illustrated in Reference (2), Figure 23.

2. Blanket-Grid to Guide-Tube

The blanket-grid to guide-tube specimen (Figure 2) consisted of a Zircaloy screw which clamped an AM-350 grid mounting tab to a Zircaloy plate. The female threads were located in the plate (which represented the

guide tube) and the plate was recessed at the tab location. The grid tab was deflected into a $\sim .010$ inch deep recess in the shell by the Zircaloy screw. This joint was locked by a small Zircaloy pin installed at an angle of about 45° through the head of the screw into the plate. The hole for the pin was not drilled completely through the plate to provide a means to capture the pin. The pin was then lock welded to the screw head to complete the assembly of the joint. The threads in the Zircaloy specimens for this assembly type and for the seed-shell to post and seed-rod to baseplate were machined by the techniques developed to provide maximum corrosion resistance for unpickled surfaces, Reference (1). The threads in these specimens were not pickled prior to corrosion testing. The threaded components received the same 3 day 680°F pure water corrosion test as the other Zircaloy components. This fastened joint is also depicted in Figure 26 of Reference (2).

3. Seed-Shell to Post

The seed-shell to post specimen (Figure 3) consisted of three Zircaloy components, a screw, a plate, and a support post. The screw clamped the plate, which represented the seed shell, to a support post. The plate was deflected into a shallow ($\sim .005$ inch) recess in the post, centered longitudinally on the screw hole, as the screw was tightened. This joint was locked by two spot welds between the screw and the plate at the outer edge of the screw head. This design is shown in Figure 23 of Reference (2).

4. Shear-Key to Guide-Tube

The shear-key to guide-tube specimen (Figure 4) had a NiCrFe Alloy 600 shear key strut clamped to the plate (simulating the blanket guide tube) by the shear key and two bolts. The 17-4 PH shear key had a circular ledge on the outer diameter which fits into a circular ledge in the Zircaloy plate. The key was loaded against the shell ledge by the two NiCrFe X-750 bolts that passed through holes in the shear key strut. The bolts also passed through holes in a 304 stainless steel locking cup that was crimped to the bolt heads and to the strut to lock the bolts. This joint design is illustrated in Figure 26 of Reference (2).

5. Seed-Top-Baseplate Bolt

The seed-top-baseplate bolt specimen (Figure 5) consisted of a 17-4 PH bolt that clamped two Zircaloy components (simulating the lugs on the support post and on the seed shell) between a 348 stainless steel support shaft and a NiCrFe alloy 600 baseplate. The female threads were located in the baseplate. The bolt head fits into a 304 stainless steel locking cup which was within a recess in the 348 stainless steel support shaft. The locking cup was crimped to the support piece and the bolt head to lock the bolt. This joint is shown in Figure 23 of Reference (2).

6. Seed-Rod to Baseplate

The seed-rod to baseplate specimen (Figure 6) was composed of a Zircaloy rod end with male threads that was clamped to a ledge in a NiCrFe Alloy 600 baseplate with a Zircaloy nut. The nut and rod end were locked together by crimping their concentric sleeves just beyond the threads. This design for the reflector end connector is shown in Figure 27 of Reference (2) and the seed design is essentially the same but smaller.

B. Test Conditions

The hydriding test specimens were exposed to high temperature, high pressure water with water chemistry controlled as in a pressurized water reactor. The test duration for hydriding evaluation was 60 days. This period was judged to be sufficient to show if any of the joints were subject to accelerated hydriding. Data in Reference (1) indicate that the 60 day test period is sufficient to show accelerated hydriding, in fact 20 to 25 days at elevated temperature was shown to produce the bulk of hydriding that might occur in a particular test run. The temperature was held at $520^{\circ} \pm 5^{\circ}\text{F}$ and the pressure at 2000 ± 100 psig. Water chemistry was controlled to a pH of 10.1 to 10.3 by ammonia and the hydrogen concentration was held near 60 cc H_2/kg water.

Nitrogen was controlled to a maximum concentration of 40 cc N₂/kg water while oxygen, chloride ion, and fluoride ion concentrations were each maintained at <0.1 ppm. Some of the specimens exposed to the relaxation conditions of 600 ± 5°F and 2800 ± psig were also evaluated for hydriding as indicated in Table I. Water chemistry for these specimens was the same as for the 520°F test conditions.

Some of the specimens (Table I) were presoaked in a potassium tetra borate (PTB) solution to simulate a possible nuclear shutdown method. Under these postulated conditions the reactor coolant would be poisoned with boron (as PTB) to maintain a safe shutdown margin. The boron would then be removed by a feed-and-bleed technique to a low level, and the demineralizer would further reduce the boron concentration. Although the core was installed in Shippingport without use of PTB, the exposure to PTB is of interest since the core could potentially be exposed to PTB by the reactor safety shutdown system during core operations.

A boron concentration of 8000 to 8100 ppm as potassium tetraborate was used for the 5 day PTB soak period with the pressure maintained at 300 ± 10 psig with nitrogen. The temperature was 75°F to 85°F. The specimens were not rinsed following the soak period except for being placed in a container of Grade A water until insertion for their test exposure. The PTB soaked specimens were tested in a separate autoclave from the regular specimens to prevent cross contamination of the soaked and unsoaked specimens.

C. Hydride Evaluation Technique

Specimens were sectioned without disassembly along the longitudinal axis of the fasteners and mounted for metallographic examination following test exposure. The metallographic mounts were polished and etched for zirconium hydride evaluation, and 250X magnification photomicrographs were taken to determine the hydride levels in the specimens by comparison with visual standards. Photomicrographs were taken to show the highest and typical concentrations of hydrides for each specimen with highest concentrations for

TABLE I
REM-20 HYDRIDE EVALUATION RESULTS

Specimen	Assembly Fig. No.	Material ⁽¹⁾ Combination	Serial Nos.	PTB Presoak	Estimated ⁽⁴⁾ Hydride Concentration	
					Pre-test	Post-test
Seed Rod to Baseplate	1	AM-350 (4.3%)	89-1107	No	25	25 (Fig. 7)
		AM-350 (4.3%)	-1113	No		
		Zircaloy-4	-1108	Yes	Fig. 9	(Fig. 8)
		304 SS (8-12%)	-1109	Yes		
Blanket Grid to Guide Tube	2	Zircaloy-4	89-1127	No	25	25 (Fig. 11)
		AM-350 (4.3%)	-1128	No	Fig. 10	
		Zircaloy-4	-1126	Yes		(Fig. 12)
Seed Shell to Post	3	Zircaloy-4	89-1184	No	25	50 (Fig. 13)
		Zircaloy-4	-1185	No		
		Zircaloy-4	-1137	Yes	Fig. 16	
			-1139	Yes		50 ⁽⁵⁾ (Fig. 14)
Shear Key to Guide Tube	4	NiCrFe Alloy X-750 (73%)	89-1180	No	25	25 (Fig. 18)
		Zircaloy-4	-1178	Yes	Fig. 17	50 (Fig. 19)
		17-4 PH SS (4.6%)				
Seed Top Base- plate Bolt	5	17-4 PH SS (4.6%)	89-1162	No	50	25
		348 SS (9-13%)	-1163	No	Fig. 22	(Fig. 20)
		Zircaloy-4	-1160	Yes		(Fig. 21)
		NiCrFe Alloy 600 (78%)				
Seed Rod to Baseplate	6	Zircaloy-4	89-1147	No	50	50 (Fig. 24)
		NiCrFe Alloy 600 (78%)	-1142	Yes		50 (Fig. 25)
		Zircaloy-4	-1146 ⁽²⁾	No	Not known	150 (Fig. 27)
			-1204 ⁽³⁾	No		50 (Fig. 26)

(1) The male threaded component is listed first, clamped component second and the female threaded component third. The value in () following the non-Zircaloy components is the approximate nickel content in the material.

(2) Exposure: 120 days at 600°F.

(3) Exposure: 85 days at 520°F.

(4) These estimates are discussed in Section II.C - Hydride Evaluation Technique.

(5) Hydride concentration in lock weld zone.

each specimen listed in Table I. A 25 ppm value indicates an estimated zirconium hydride level of approximately 25 ppm and definitely <50 ppm. A 50 ppm value indicates a hydride concentration >25 ppm and <100 ppm. The 150 ppm value indicates an estimated level of $\geq$ 100 ppm but <200 ppm. Visual standards for hydrides in Zircaloy-4 were developed at Bettis from out-of-pile corrosion tests. These standards were provided to aid in the assessment of hydriding in irradiated LWBR cladding and were used in evaluating the results of this test.

The pre-exposure hydride level for the Zircaloy components was established from photomicrographs of Zircaloy reference components which were processed with the exposed specimens but not assembled nor exposed to the 60 day exposure to 520°F water. These reference components were procured from the same vendor using the same Zircaloy starting material and machining technique. The reference components were then processed through corrosion testing with the test specimen Zircaloy components. The hydride levels in these components were estimated from the metallographic sections in the same fashion as for the test specimens.

D. Hydride Results

The comparison of post-test photomicrographs of the Zircaloy components to the photomicrographs of the reference components shows that no hydrogen level increase indicative of accelerated hydriding occurred. In addition, no discernible effect was found for the specimens which had been presoaked in PTB. The pre-test (reference) and post-test estimated hydride levels are listed in Table I. In most specimens, the maximum and typical hydride concentrations were about the same (25 to 50 ppm) and the hydrides were uniformly distributed throughout the specimen. This hydride uniformity agreed with results from other isothermal tests of threaded Zircaloy components, Reference (1). The results for each joint type are described below and typical photomicrographs of each are included. The specimens were exposed for 60 days and mounted for metallography without disassembly.

1. Seed-Grid to Post

The seed-grid to post specimen 250X photomicrographs of the etched Zircaloy component in this joint for two test specimens are shown in Figures 7 and 8. Figure 7 shows the hydride level in Specimen 89-1107 which was not pre-soaked in PTB and Figure 8 shows Specimen 89-1108 which did receive the PTB presoak. Comparison of Figures 7 and 8 illustrates the lack of a discernible effect on hydriding resulting from the PTB presoak of Specimen 89-1108. Comparison of the pre- (Figure 9) and post-photomicrographs shows about 25 ppm hydrides in both such that no apparent tendency to accelerated hydriding occurred. Accelerated hydriding was not expected to occur in this joint since the Zircaloy component was clamped between 304 stainless steel on both sides and no relative motion between the stainless steel and the Zircaloy occurred at assembly. No accelerated corrosion or hydriding is predicted to occur when the Zircaloy corrosion film remains intact and no nickel bearing material is transferred to the Zircaloy surface (Reference (1)). The other two specimens of this type (one with and one without PTB presoak) had the same hydride levels as the two described above.

2. Blanket-Grid to Guide-Tube

The blanket-grid to guide-tube specimen 250X photomicrographs are Figures 10, 11, and 12. They show the starting zirconium hydrides in a blanket grid screw, the hydrides in the screw in Specimen 89-1127 (not presoaked in PTB) and hydrides in the screw in Specimen 89-1126 (presoaked in PTB) respectively. The hydride levels were comparable in all three photomicrographs (about 25 ppm) and indicate that no massive accelerated hydriding occurred. This specimen type would be more likely to hydride than the seed grid to post specimen since there are unpickled Zircaloy threads involved and the unpickled underside of the screw head rubs against the AM-350 grid tab during torquing. The relative motion of the Zircaloy under load against the nickel bearing AM-350 presents the potential for nickel transfer to the Zircaloy surface. Such transfer has been shown to result in accelerated hydriding; however, as shown in the figures, there was no evidence of massive accelerated hydriding in these specimens. Figures 28, 29, 30, and 31 show the lock weld condition for this type of joint and these figures are discussed in paragraph II.D.7.

3. Seed-Shell to Post

The seed-shell to post specimen 250X photomicrographs are Figures 13, 14, 15, and 16. They show respectively the zirconium hydrides in the screw thread of Specimen 89-1184 (not presoaked in PTB), the screw to shell weld zone of Specimen 89-1139 (presoaked in PTB), a comparison of standard zirconium hydride preparation to the anodized-polarized light preparation, and the starting hydride level for a screw. This specimen type consists of all Zircaloy components; screw, shell, and post.

Since the hydride concentrations were low, some metallographic mounts were anodized and viewed under polarized light to make the zirconium hydride precipitates easily discernible. Figure 15a illustrates a typical area from a seed shell to post screw with the standard etch and Figure 15b shows the same area with the anodized-polarized light technique, which is also known as Pickle-sheimer etch. The slight increase (approximately 25 ppm) from pre-test to post-test hydride concentration is not considered to be indicative of massive, accelerated hydriding. In this range of hydride concentrations, it is not abnormal for the estimated level to vary by 25 ppm from sample-to-sample of the same material when using metallographic estimates of hydride concentrations. The shell component was pickled on the angled surface that the screw head bears against; however, the threads in both the screw and the post were not pickled prior to corrosion prefilming. The angled surface of the screwhead was not pickled prior to prefilming.

4. Shear-Key to Guide Tube

The shear-key to guide-tube specimen 250X photomicrographs are Figures 17, 18, and 19. They show the starting hydrides in a Zircaloy shell representing the blanket guide tube, the hydrides in the shell part of Specimen 89-1180 (not presoaked in PTB), and in Specimen 89-1178 (with PTB presoak) respectively. These figures show a slight (25 ppm) increase in hydrides from pre- to post-test but no apparent effect resulting from the exposure to PTB. This slight increase in hydride level is not indicative of massive, accelerated hydriding. This joint type clamps the Zircaloy guide

tube against a NiCrFe shear key strut using a 17-4 PH shear key. The Zircaloy does not receive any smearing contact with either the NiCrFe or the 17-4 PH as a result of assembly. The Zircaloy in this joint was pickled prior to corrosion prefilming. Two surfaces of the Zircaloy component did experience a sliding type of loaded movement of small amplitude against the 17-4 PH shear key and against the NiCrFe shear key strut as a result of differential thermal expansion but the surfaces showed no evidence of accelerated hydriding.

5. Seed-Top Baseplate Bolt

The seed-top-baseplate bolt specimen 250X photomicrographs are Figures 20, 21, and 22. They show the hydrides in the shell lug of Specimen 89-1163 (not presoaked in PTB) and the starting hydride for the shell lug, respectively. In these rather large components, there was no evidence of accelerated hydriding even for the specimen presoaked in PTB since the indicated hydride level was slightly lower in the components receiving exposure than in the reference component. Since a decrease in hydrogen due to exposure is unlikely, the sample-to-sample variation in hydrogen as estimated by metallography is illustrated. These specimens were not expected to exhibit accelerated corrosion or hydriding since there was no smearing of the prefilm on the two Zircaloy components in this joint. These two Zircaloy components are clamped between 348 stainless steel and NiCrFe with no relative rotation involved between the components mating with Zircaloy.

6. Seed-Rod to Baseplate

The seed-rod to baseplate specimen 250X photographs are Figures 23, 24, 25, 26, and 27. They illustrate, in order, the starting hydride concentration in a rod nut, the post test hydrides in a nut from 89-1147 (not presoaked in PTB), a fuel rod end closure from 89-1142 (presoaked in PTB), a rod nut from 89-1146 (not presoaked in PTB) and a rod nut from 89-1204 (not presoaked in PTB). These figures show 50 ppm hydrides in pre- and post-test photomicrographs and illustrate that the fuel rod nuts and end closures which had acceptable corrosion film prior to test exposure (Figure 23) did not have an appreciable increase in hydrides. The two seed rod to baseplate

specimen assemblies, which were tested and examined for hydriding, were sectioned while still assembled. Sections were made along the longitudinal axis of the fasteners and all ten nuts and endclosure stems were examined. Two nuts from relaxation testing were also sectioned longitudinally. Figures 23 through 27 show the highest hydrides found in each specimen examined.

This joint had the highest potential for accelerated hydriding of those tested. The face of the nut which bears on the NiCrFe baseplate was loaded to a high stress ($\sim 60,000$ psi) against the nickel bearing baseplate with a smearing type contact. The transfer of nickel to Zircaloy component through the broken corrosion prefilm has been shown to result in accelerated corrosion and hydriding as reported in Reference (1). While it was beyond the scope of the REM-120 test, the use of chrome coatings to prevent the transfer of nickel to Zircaloy was investigated and discussed in Reference (1).

The highest hydride concentration found in REM-120 testing is shown in Figure 26 for a nut from specimen 89-1146. The center of the face of the nut sleeve which bears against the NiCrFe baseplate is shown. The relatively high hydride concentration, estimated to be between 100 to 200 ppm, is attributed to the fact that this particular fuel rod nut had considerable white corrosion product in the inside diameter of the sleeve portion prior to the 600°F, 120 day test exposure. This indicates that either acid staining or air entrapment occurred during the pickling operation. These conditions would result in a Zircaloy surface which would corrode at a high rate and thereby tend to produce more hydriding than a properly pickled and corrosion tested surface. A component with this amount of white corrosion product following the standard corrosion test would not be used in core or as a component in the hydriding portion of this test. Since this nut was used in REM-120 in a specimen assembly which was exposed for determination of relaxation properties, the corrosion prefilm quality was not an acceptance criterion for this component. No untested nut with this amount of white corrosion product in the inside of the sleeve was available to demonstrate reference hydride levels.

7. Lock Welds

The photographs and microphotographs of the lock welds are listed in Table II. Two of the six specimen types were locked by welding; the blanket-grid to guide-tube and seed-shell to post specimens. Each of these joints was locked by the welding of Zircaloy-to-Zircaloy.

TABLE II
REM-120 LOCK WELD PHOTOGRAPHS

<u>Specimen Type</u>	<u>Specimen No.</u>	<u>Lock Weld Photographs</u>	
		<u>Pre-Test</u>	<u>Post-Test</u>
Blanket-Grid to Guide-Tube Specimen	89-1128	Fig. 28	Fig. 31
	-1126 Fig. 29	Fig. 30	
Seed-Shell to Post Specimen	89-1184	Fig. 32	Fig. 33
	-1137 Fig. 35	Fig. 34	
	-1133	Figs. 36 & 37	

(a) The blanket-grid to guide-tube lock weld is shown in Figures 28, 29, 30 and 31. A slight amount of white or gray corrosion film can be seen after test in Figures 30 and 31, occurring in streaks at the edge of the heat-affected zone around the weld. An apparently gray or white corrosion spot in the center of the weld (Figure 31) is actually a light reflection since a visual examination after test revealed no white corrosion in the weld. This weld was made inside a plastic weld box which had been purged with argon. The weld was made with Tungsten Inert Gas (TIG) by hand at 10 volts - 80 amperes for approximately 1-2 seconds after the screw and guide tube had been drilled and the locking pin inserted into the joint. A slightly different set of parameters was used in the fabrication of the LWBR core for this TIG weld. The corrosion prefilm was not removed from the pin prior to making the lock weld. No loosening of this joint nor yielding of the tab occurred as a result of the locking method used in the test. During the metallographic examination, the mounts were ground in 10 to 15 mil increments and visually examined at each increment at 50X. No cracks were found in these specimens.

(b) The seed-shell to post specimen lock weld is shown in Figures 32, 33, 34, 35, 36 and 37. The low magnification photos show that a slight amount of gray/white corrosion product occurs at the outer edges of the heat-affected zone of the welds but none occurs in the weld itself. Typical hydrides in Specimen 89-1137 weld zone are shown in Figure 14. Corrosion films on the weld were about .03 and .04 mils thick before and after test, respectively; this agrees with the slight hydride increase in these specimens. These welds were also made in a plastic weld box which was purged with argon prior to welding at 10 volts - 80 amperes for approximately 1-2 seconds by a hand held TIG torch. The corrosion prefilm was not removed from the mating Zircaloy components prior to lock welding. Specimen 89-1184 has two welds per screw, the other specimens have one weld per screw so located that the 304 stainless steel shim would exert approximately 175 pounds of force on the screw to shell lockweld when the specimen was heated to temperature. The 175 pounds represented the shell to post load generated on heatup and cooldown by the different deflections of the shell and post. Specimen 89-1133 was cycled from 75°F to 600°F and back to 75°F for 120 cycles to simulate plant heatup and cooldowns. This specimen was then ground in 10 to 15 mil increments and visually examined for cracks at each increment. No cracks were found; Figures 36 and 37 show 12X and 32X photos of one such increment for 89-1133.

III. LOAD RETENTION TEST (RELAXATION)

Twelve REM-120 specimens were assembled primarily for load retention evaluation. These specimens were assembled in the same manner as the hydriding evaluation specimens except that the load retention specimen fasteners were not locked so that the loosening torque could be measured after test exposure. The post-test loosening torque was compared to the pre-test torque to obtain a qualitative measure of the load in the fastener after test exposure. For the shear key to guide tube specimens this was the only measure of load retention and provided secondary data points for the rest. The prime method for determining the amount of relaxation was to measure the changes in the length of the bolt as a result of assembly and of test exposure. There

were two specimens of each of the six types tested in this portion of the test. Table III lists these specimens, the fastener material, serial numbers, the component measured, the measured test relaxation, and the predicted relaxation. The prediction of thermal relaxation was derived from curved beam tests as described in Section III.B.

The relaxation specimens were exposed to 600°F water for 60 days with the exception of the seed rod to baseplate specimen 89-1146 which received 120 days at 600°F. Water chemistry was controlled to the same requirements as used in the hydriding portion of the test (Section II.B).

A. Load Retention (Relaxation) Test Results

1. Seed-Grid to Post

The seed-grid to post specimens had measured relaxations for the two specimens of 10.7% and 15.6% for an average of 13%. This compares to the predicted (Section III.B.1) AM-350 thermal relaxation of 10% for 60 days at 600°F. The relaxation in these fasteners was determined by dividing the amount of plastic stain in the bolt after test exposure by the amount of strain introduced at assembly. These bolts were torqued to 36 inch/pounds at assembly to produce approximately 480 pounds of clamping force on the 0.375 inch thick AM-350 lug and the 0.375 inch thick Zircaloy component. This resulted in a tensile stress in the bolts at assembly of about 17,000 psi which is well below the AM-350 yield strength at room temperature. These bolts had a nominal shank diameter of 0.190 inch and a nominal shank length of 1.225 inch.

2. Blanket-Grid to Guide-Tube

The blanket-grid to guide-tube specimens had measured relaxations for the two specimens of 5% and 14% for an average of about 10%. These values compare favorably with the 10% relaxation predicted (Section III.B.1) for AM-350 at 600°F for 60 days. The relaxation for these fasteners was determined by dividing the change in the bow of the unrestrained tabs from

before to after exposure by the tab deflection at initial assembly. The shape of the tabs was found by profiling the tabs along two longitudinal traces on either side of the screw head and averaging the results. The spread in the indicated relaxation values is a result of the four sets of longitudinal traces not taking exactly the same path along the top surface of the tab. Traces were taken before the initial assembly, following initial assembly, following test exposure (before disassembly) and again after test exposure and subsequent disassembly. Comparison of the pretest and post test profiles of the assembled tabs showed no evidence of the tab separating from the guide tube at the screw locations. The stress level in the tabs was approximately 48,000 psi. The design of this connection is discussed in Reference (3).

The tabs for these specimens were fabricated from low carbon AM-350 sheet, the material was 0.015 inch thick in specimen 89-1124 and 0.013 inch thick in specimen 89-1125. Each tab consisted of two pieces 0.580 inch wide and 1.695 inch long. These pieces were spot welded together, decarburized and given a braze heat treatment which consisted of heating in a vacuum to $\sim 2100^{\circ}\text{F}$. Braze alloy was not applied to the tabs prior to the braze cycle and the 0.340 inch diameter attachment holes were drilled after the heat treatment was completed. The fabrication of these tabs followed the procedure and used the materials employed in the fabrication of the LWBR Core.

3. Seed-Shell to Post

The seed-shell to post specimens had measured relaxations of the Zircaloy-4 shell in the two specimens, 89-1134 and 89-1136, of 28% and 21% for an average of $\sim 24\%$. This compares favorably to the predicted (Section III.B.3) thermal relaxation of 33% for Zircaloy-4 at 600°F for 60 days. Relaxation for Zircaloy was predicted using curved beam test results as discussed in Section III.B.

The relaxation of this connection was determined by dividing the change in unrestrained bow of the shell from pre- to post-test by the deflection at initial assembly. It was necessary to account for some plastic set in the shell at 600°F in the calculation of relaxation; about 1.1 mils of plastic set resulted at 600°F in the two relaxation specimens. The amount of deflection which results in the stress in the shell to reach yield for 600°F was calculated to be 2.9 mils. Therefore, when the assembled shell deflection was more than 2.9 mils, a deflection of 2.9 mils was used as the initial value of deflection. The shape of the tabs was determined by profiling the shell on two longitudinal traces on either side of the screw head.

The components in this specimen were Zircaloy-4, except for the 304 stainless steel shim. The 0.375-16 flat head screw was torqued to $16 \pm .5$ inch-pounds which deflected the 0.080 inch thick shell into a nominally 0.005 inch deep by 1.103 inch long recess in the post that contained the tapped hole.

4. Shear-Key to Guide Tube

The shear-key to guide-tube specimen results indicated very little thermal relaxation had occurred. This specimen contained two 0.250-20 thread by 0.440 inch long bolts made from NiCrFe alloy X750. Since these bolts had a very short ($\sim .185$ inch) strained length, the only practical means to determine the load retention was by measurement of torque. The break-away torque was measured after test exposure and compared to the pretest break-away torques obtained in assembly of the specimen. These bolts were tightened three times at assembly to 35 ± 2 inch-pounds and the break-away torque recorded for the two loosening involved. The two bolts in this specimen had second break-away torques of 15 and 18 inch-pounds at assembly. These same bolts had break-away torques of 25 inch-pounds following the 60 day, 600°F exposure. Although this method produces essentially qualitative results, it does indicate that these 0.250-20 bolts relaxed very little during the 60 day exposure. The increase in loosening torque is believed to be in part due to the normal resistance to rotation of the mating surfaces in the threads and under the bolt head following an extended period at high temperature. The predicted relaxation for the NiCrFe alloy X750 material is < 5%. (Section III.B.2)

5. Seed-Top-Baseplate Bolt

The seed-top-baseplate bolt specimens had measured relaxations of the two top baseplate bolts in specimens 89-1157 and 89-1161 of 18.2 and 8.5% for an average of 13.2%. This compares to the assumed (Section III.B.1) value for 17-4 PH of 10% for the 60 days at 600°F. The scatter in the data is due to the raising of burrs on the head of the bolt and measurement accuracy. The relaxation was calculated by dividing the amount of plastic set in the bolt from pre- to post-test by the stretch at initial assembly. A test was made to determine the plastic strain occurring in the bolts resulting from assembly only. This test used two new bolts which were assembled by the same procedure as the test specimens and disassembled without test exposure. A 0.2 mil lengthening was found and was subtracted from the indicated plastic set in the calculation of relaxation for the exposed specimens. The tensile stress at assembly was about 27,100 psi, which is well below yield for this 17-4 PH material.

This specimen used a 0.500-13 bolt to clamp two Zircaloy lugs between a NiCrFe alloy 600 baseplate and a type 348 stainless steel support shaft. The female threads were in the NiCrFe baseplate. The bolts were torqued to 60 ± 5 foot-pounds at assembly.

6. Seed-Rod to Baseplate

The seed-rod to baseplate specimens had measured average relaxation of 36% for assembly 89-1143 (60 days) and an average relaxation of 41% for assembly 89-1146 (120 days). There were two seed rod to baseplate specimens tested. Each assembly included two standard (long) and three short rod end closures and nuts. The individual data are contained in Table IV. Predicted relaxations (Section III.B.3) are 33% for 60 days and 37% for 120 days at 600°F for Zircaloy-4 material. The tensile stress in the end closure shanks ranged from 48,000 to 58,000 psi at assembly (cold) and from 13,200 to 14,300 psi (hot). The preload specified in these fasteners is in the plastic range and is set high enough so that there would be sufficient load left after exposure equivalent to that of LWBR core operation.

An example of the calculation of relaxation follows for the long end closure from assembly 89-1143. The beginning of test (B.O.T.) stretch of 5.43 mils resulted when the nut was tightened to 122° rotation with 48 inch-pounds of torque being required. This 5.43 mils elongation is equal to 0.326% strain, the B.O.T. strain. Now, the end-of-cycle (E.O.C.) strain (elastic strain remaining after a cycle to 600°F as a function of the initial, B.O.T., strain) was found to be 0.130% for the 0.326% B.O.T. strain. A separate test was performed to establish the amount of elastic strain remaining in an end connector as a function of initial strain following a temperature cycle from room temperature to 600°F and back to room temperature. The E.O.C. strain is converted to an E.O.C. elongation (stretch) of 1.95 mils, which is used as the initial amount of elastic stretch for relaxation determination. The measured post-test elastic stretch of 1.30 mils is subtracted from the 1.95 E.O.C. stretch to show a relaxation (loss of elastic stretch) of 0.65 mils. The relaxation is then found to be $(0.65 \div 1.95) \times 100 = 33\%$.

The nut tightening columns in Table IV give the torque (inch-pounds) required to tighten the nut to the indicated rotation (degrees) after initially tightening the nuts to 2.5 ± 0.5 inch-pounds to seat the nuts and closures on the NiCrFe alloy 600 baseplate. In these specimens, the 0.100 inch thick NiCrFe baseplate was clamped between the Zircaloy-4 end closure and the Zircaloy-4 nut. The end closure had a 0.170 inch diameter shank and a strained length of 1.49 inch for the long closures and 0.97 inches for the short closures. The nuts had an integral sleeve between the 0.216-28 threads and the bearing surface. This sleeve was 0.025 inch thick with a 0.280 inch outside diameter and was 1.40 inch long for the long nut and 0.875 inch long for the short nut.

B. Predicted Thermal Relaxation

Out-of-pile tests at Bettis with curved beam specimens have shown that the thermal stress relaxation of most reactor materials is dependent upon the initial stress level. The curved beam tests consisted of a group of narrow, curved beams about 6 inches long. Each beam was formed with a radius

so that when the beam was installed in the test holder and straightened out, the desired outer fiber bending stress was produced. The change in curvature of the unrestrained beams after test exposure was measured and used to calculate relaxation. The results of these tests are shown in Figures 38 and 39 and indicate that the thermal relaxation tends to level out after a short period (approximately 3 days) at 600°F. Most of these out-of-pile thermal relaxation tests on materials, other than Zircaloy, were done for higher initial stress levels than are encountered in the REM-120 test. The prime reason for this was the need to obtain data for grid spring materials where stresses often are in the plastic range.

1. AM-350 and 17-4 PH

The relaxation of two different components fabricated from AM-350 material were measured in the REM-120 test and the results are listed in Table III. The first component was the seed grid bolt. These bolts attached the lugs on the exterior boundary of a seed grid to the support posts. These bolts were tightened in the REM-120 test to an initial stress of approximately 17,000 psi. No thermal relaxation data from curved beam testing for an initial stress range were available; however it was judged that 10% thermal relaxation would be a conservative estimate for this component for the 60 day (1440 hours) exposure in 600°F water. The curved beam test data for AM-350 thermal relaxation at 600°F shown on Figure 38 were used as the basis for this estimate. The predicted values were chosen to represent an upper bound for relaxation. Figure 38 shows the stress dependency of AM-350 relaxation. The lower range stress data were used to predict the AM-350 relaxation for the REM-120 specimens.

The second AM-350 component tested in the REM-120 test was the blanket grid to guide tube tab. These tabs were used to connect the inner boundary of the blanket grids to the guide tube. There were two tabs used on each of the six sides of the hexagonal guide tube for each grid. The tabs were deflected over a span of 1.062 inches into a nominally 0.010 inch deep recess in the guide tube; the calculated stress was approximately 48,000 psi. Again, no curved beam data were obtained for this stress level and the 10% value was judged to be a conservative estimate for this component.

The thermal relaxation of the 17-4 PH component, the seed top baseplate bolt, was taken to be the same as the 10% used for AM-350 since these materials are similar in composition. No curved beam testing of 17-4 PH material was done.

2. NiCrFe Alloy X750

The thermal relaxation of NiCrFe Alloy X750 was measured for one specimen type in this test. Out-of-pile curved beam tests of this material have demonstrated that these heat resisting materials result in no measurable thermal relaxation at the 600°F temperature used in the REM-120 test. Therefore, the predicted relaxation was given as < 5%. REM-120 test results are consistent with this prediction. The REM-120 specimens were assembled to an initial stress of about 24,000 psi.

3. Zircaloy-4

The thermal relaxation of Zircaloy-4 was measured for three different specimen types in this test. The curved beam test data shown in Figure 39 for Zircaloy-4 indicate relaxation values of 33% and 37% for 600°F at 60 days and 120 days, respectively. The values for a transverse specimen with a stress of 9.7 KSI from Figure 39 were used since they were the highest values measured in the curved beam tests for Zircaloy-4 thermal relaxation. The curved beam tests did not take the specimens into the plastic range at assembly as did the REM-120 test components. This is a possible explanation for the slightly higher than predicted relaxation for the seed rod end connector data. The initial (hot) REM-120 stresses were approximately at yield strength for the seed shell to post joint and about 13,200 to 14,300 psi for the seed end connectors after taking into account the plastic deformation due to short time exposure to 600°F.

TABLE III
REM-120 LOAD RETENTION (RELAXATION) SPECIMENS

Specimen Type	Fastener Material and Thread Size	Serial Number	Number of Specimens Tested	Component Measured	Relaxation (%)	
					Test	Predicted ⁽¹⁾
1. Seed Grid to Post	Am-350 .190 - 32	89-1111 -1112	2	AM-350 Bolt	10.7 15.6 Avg. 13.2	10
2. Blanket Grid to Guide Tube	Zircaloy-4 .312 - 24	89-1124 -1125	2	AM-350 Tab	5 14 Avg. 10	10
3. Seed Shell to Post	Zircaloy-4 .375 - 16	89-1134 -1136	2	Zircaloy-4 Shell	31.7 31.4 Avg. 31.6	33
4. Shear Key to Guide Tube	NiCrFe Alloy X750 .250 - 20	89-1179	2	NiCrFe Alloy X750 Bolt	Confirmed low relaxation rate <5	
5. Seed Top Baseplate Bolt	17-4 PH .500 - 13	89-1161 -1157	2	17-4 PH Bolt	8.3 18.2 Avg. 13.2	10
6. Seed Rod to Baseplate ⁽²⁾	Zircaloy-4 .216 - 28	89-1143 -1146 ⁽³⁾	5 5	Zircaloy-4 End Closure	36 41	33 37

(1) Predicted relaxation values are based on data from curved beam tests as discussed in Section III.B.

(2) Table IV gives the results for the individual nuts and end closures for these two specimen assemblies which each contained 5 connectors.

(3) Exposure: 120 days at 600°F.

TABLE IV
REM-120 SEED ROD TO BASEPLATE SPECIMEN (ZIRCALOY-4) RELAXATION

Rod End Closure												
Specimen Assembly & Exposure	Type	B.O.T. (2)	B.O.T. (2)	E.O.C. (3)	E.O.C. (3)	Post (4)	Mils (5)	%	Avg. Relax.	Predic- ted Relax.	Nut Tightening	
		Stretch (mils)	Strain (%)	Strain (%)	Stretch (mils)	Test Elastic (mils)	Relaxed -	Relax- ation %			Torque in-lb	Angle degrees
89-1143 ⁽¹⁾ 60 days at 600°F	Long	5.43	.362	.130	1.95	1.30	0.65	33	36	33	48	122
	Short	4.91	.505	.135	1.32	0.66	0.66	50			55	111
	Short	4.93	.505	.135	1.32	0.90	0.42	32			55	110
	Short	5.46	.577	.138	1.35	0.96	0.39	29			53	110
89-1146 120 days at 600°F	Long	6.12	.408	.132	1.98	0.48	1.50	76	41	37	54	123
	Long	5.86	.391	.132	1.98	1.26	0.72	36			48	122
	Short	5.58	.572	.137	1.34	1.09	0.25	19			55	111
	Short	5.83	.598	.138	1.35	1.16	0.19	14			58	111
	Short	6.75	.693	.142	1.39	0.58	0.81	58			46	110

- (1) One of the long end closures in this specimen was not included due to an error in the initial length measurement.
- (2) B.O.T. Stretch is the measured elongation in mils at initial assembly and B.O.T. strain is the % strain resulting.
- (3) E.O.C. Strain is the % strain remaining in the end closure following one cycle to 600°F and E.O.C. Stretch is the corresponding elongation in mils.
- (4) Post Test Elastic is the measured elastic elongation of the end closure after test exposure.
- (5) Mils Relaxed is the difference between the E.O.C. stretch and Post Test Elastic elongations and is the loss of elastic strain through relaxation.

IV. CONCLUSIONS

A. Hydriding Results

Results of metallographic examination of the Zircaloy hydriding specimens have shown no evidence of massive accelerated hydriding, even for those specimens that were presoaked in a water solution of 8000 ppm boron as potassium tetraborate (PTB) prior to their 60 day test exposure in 520°F water. The hydride concentrations in the Zircaloy components were essentially unchanged from pretest to post test and were estimated to be in the 25 to 50 ppm range. The affirmative results of this test add confidence in the in-pile performance of the fastener, although the results cannot be used to assure satisfactory in-pile behavior. Note, however, that accelerated hydriding in the end closure to base plate connection has been identified in subsequent out-of-pile testing and was reported in reference (1). At the time the REM-120 test was performed, the hydriding of the face of the nut was judged to be of no adverse consequence since the applied stress was compressive, i.e. no failure of the joint would result from hydriding. Therefore, the REM-120 specimens were longitudinally sectioned for hydride evaluation to obtain an overall check for hydride concentration and distribution. This could have let small spots of hydriding on the face of the nut go undetected. The later test, reference 1, took sections incrementally starting at the end face, thin layers of hydriding were found in this area of the nuts in reference (1) testing.

B. Relaxation Results

Measurements of thermal relaxation of the fasteners after 60 days exposure to 600°F water were near the predicted values. The average relaxation values are given in Table III. The affirmative results of the relaxation testing show that the fasteners are expected to perform acceptably in core.

V. ACKNOWLEDGEMENTS

The author wishes to express his appreciation to many of his colleagues who assisted in the preparation and review of this document. Dr. E. Hillner, Mr. B.Z. Hyatt, Mr. J.J. Kearns, Mr. E.H. Schwer and Dr. J.W. Stout provided useful assistance in the original test effort and evaluation of the results. Mr. M.J. Schneider, Dr. J.C. Clayton, Mr. E.L. Miller, and Mr. R.A. Frederickson provided technical direction and assistance for preparation of this document.

VI. REFERENCES

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3. K.D. Richardson, "Summary of the Fuel Rod Support System (GRIDS) Design for LWBR", WAPD-TM-1331, February, 1979.

Figure 1 - Seed-Grid to Post Specimen Assembly

Figure 2 - Blanket-Grid to Guide-Tube Specimen Assembly

Figure 3 - Seed-Shell to Post Specimen Assembly

Figure 4 - Shear-Key to Guide-Tube Specimen Assembly

Figure 5 - Seed-Top-Baseplate Bolt Specimen Assembly

Figure 6 - Seed-Rod to Baseplate Specimen Assembly

Figure 7 - Post from Seed-Grid to Post Specimen 89-1113 After
60 Days at 520°F without PTB Presoak (Etched-250X)

Negative No. 48153-28

Figure 8 - Post from Seed-Grid to Post Specimen 89-1108 After
60 Days at 520°F with PTB Presoak (Etched-250X)

Negative No. 48153-30

Figure 9 - Reference Hydride in Post from Seed-Grid to Post Type Specimen After 3 Day Prefilming (Etched - 500X)

Negative No. 48153-27

Figure 10 - Reference Hydride in Screw From Blanket-Grid-to Guide-Tube Type Specimen after 3 Day Prefilming (Etched - 500X)

Negative No. 48153-26

Figure 11 - Screw from Blanket Grid to Guide Tube Specimen 89-1127
After 60 Days at 520°F Without PTB Presoak (Etched-250X)

Negative No. 48153-25

Figure 12 - Screw from Blanket-Grid to Guide-Tube Specimen 89-1126
After 60 Days at 520°F With PTB Presoak (Etched-250X)

Negative No. 48153-24

Figure 13 - Screw From Seed-Shell to Post Specimen 89-1184
After 60 Days at 520°F Without PTB Presoak (Etched-250X)

Negative No. 48153-23

Figure 14 - Screw from Seed-Shell to Post Specimen 89-1139 After
60 Days at 520°F with PTB Presoak (Etched-250X)

Negative No. 48153-22

Figure 15a - Screw from Seed-Shell to Post Specimen 89-1139 After
60 Days at 520°F with PTB Presoak (Etched-500X)

Negative No. 48153-21

Figure 15b - Screw from Seed-Shell to Post Specimen 89-1139, Same Area
as Figure 15a - Anodized and Viewed with Polarized Light - 400X

Negative No. 48153-20

Figure 16 - Reference Hydrides in Screw from Seed-Shell to Post Type Specimen After 3 Day Prefilming (Etched-250X)

Negative No. 48153-19

Figure 17 - Reference Hydrides in Guide-Tube from Shear-Key to Guide-Tube Type Specimen After 3 Day Prefilming (Etched 500X)

Negative No. 48153-18

Figure 18 - Guide-Tube from Shear-Key to Guide-Tube Specimen 89-1180
After 60 Days at 520°F Without PTB Presoak (Etched-250X)

Negative No. 48153-17

Figure 19 - Guide-Tube From Shear-Key to Guide-Tube Specimen 89-1178
After 60 Days at 520°F with PTB Presoak (Etched-250X)

Negative No. 48153-16

Figure 20 - Shell from Seed-Top Baseplate Bolt Specimen 89-1163
After 60 days at 520°F without PTB Presoak (Etched-250X)

Negative No. 48153-15

Figure 21 - Shell from Seed-Top-Baseplate Bolt Specimen 89-1160 After
60 Days at 520°F with PTB Presoak (Etched -250X)

Negative No. 48153-14

Figure 22 - Reference Hydride in Shell from Seed-Top-Baseplate Bolt
Specimen Type After 3 Day Prefilming (Etched 500X)

Negative No. 48153-13

Figure 23 - Reference Hydride in Nut from Seed-Rod to Baseplate
Specimen Type after 3 Day Prefilming (Etched-500X)

Negative No. 48153-12

Figure 24 - Nut from Seed-Rod to Baseplate Specimen 89-1147 After
60 Days at 520°F without PTB Presoak (Etched-500X)

Negative No. 48153-10

Figure 25 - Shank from Seed-Rod to Baseplate Specimen 89-1142 After
60 Days at 520°F with PTB Presoak (Etched-500X)

Negative No. 48153-11

Figure 26 - Nut from Seed-Rod to Baseplate Specimen 89-1146 After
120 Days at 600°F without PTB Presoak (Etched-250X)

Negative No. 48153-9

Figure 27 - Nut from Seed-Rod to Baseplate Specimen 89-1204 After
85 Days at 520°F without PTB Presoak (Etched-250X)

Negative No. 48153-8

Figure 28 - Lock Weld on Blanket-Grid to Guide-Tube Specimen 89-1128 Before Test Exposure and Without PTB Presoak (4X)

Negative No. 48153-3

Figure 29 - Lock Weld on Blanket-Grid to Guide-Tube Specimen 89-1126 Before Test Exposure and with PTB Presoak (4X)

Negative No. 48153-2

Figure 30 - Lock Weld on Blanket-Grid to Guide-Tube Specimen 89-1126
After 60 Days at 520°F with PTB Presoak (1.5X)

Negative No. 48153-4

Figure 31 - Lock Weld on Blanket-Grid to Guide-Tube Specimen 89-1128
After 60 Days at 520°F without PTB Presoak (1.5X)

Negative No. 48153-36

Figure 32 - Lock Weld on Seed-Shell to Post Specimen 89-1184
Before Text Exposure and Without PTB Presoak (2.5X)

Negative No. 48153-5

Figure 33 - Lock Weld on Seed-Shell to Post Specimen 89-1184 After
60 Days at 520°F Without PTB Presoak (5X)

Negative No. 48153-6

Figure 34 - Lock Weld on Seed-Shell to Post Specimen 89-1137 Before
Test Exposure with PTB Presoak (2.5X)

Negative No. 48153-1

Figure 35 - Lock Weld on Seed-Shell to Post Specimen 89-1137 After
60 Days at 520°F with PTB Presoak (2.5X)

Negative No. 48153-34

Figure 36 - Seed-Shell to Post Specimen 89-1133 after 120 Thermal Cycles (75° to 600°F) in Weld Zone. Presoaked in PTB (12X)

Negative No. 48153-7

Figure 37 - Seed-Shell to Post Specimen 89-1133 After 120 Thermal Cycles (75° to 600°F) in Weld Zone. Presoaked in PTB (32X) Same Area as Figure 36

Negative No. 48153-29

FRACTIONAL THERMAL STRESS RELAXATION OF AM-350 CURVED BEAMS AT 600°F

Figure 38 - AM-350 Thermal Relaxation at 600°F

Figure 39 - Zircaloy-4 Thermal Relaxation at 600°F