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EFFECTS OF
PROCESSING AND OPERATING PARAMETERS
ON THE CREEP PROPERTIES OF
SNAP REACTOR FUEL ELEMENT CLADDING
(Title Unclassified)

AEC Research and Development Report

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M-3679 (41st Ed.)

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EFFECTS OF
PROCESSING AND OPERATING PARAMETERS
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(Title Unclassified)

By

G. E. CULLEY
J. T. BERLING

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ABSTRACT

A series of 1,000-hr biaxial creep tests at 1400°F were performed on SNAP 8 reactor fuel element cladding to determine the influence of the processing and operating parameters (excluding radiation) on the creep characteristics of the cladding. The parameters tested were:

- 1) Variations in ceramic hydrogen barrier coatings
- 2) Grain size
- 3) Hydrogen permeation
- 4) Stress level
- 5) Flowing NaK.

The tests were conducted over a range of hoop stresses from 2,500 to 12,000 psi and the resulting creep data were compared with INOR-8 data obtained in air and molten salt. The general conclusion for these accelerated tests was that the SNAP 8 reactor parameters caused no gross effects upon the creep properties of the cladding material. However, trends for certain parameters were detectable (particularly at lower stress levels), and may be important considerations in long-term creep.

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I. INTRODUCTION

In the SNAP reactors developed at Atomics International, the fuel material (zirconium-uranium-hydride) is separated from the NaK coolant by a thin metal cladding tube. This cladding tube must afford efficient heat transfer, have a reasonably low neutron capture cross section, maintain complete separation of fuel and coolant, possess good corrosion resistance in NaK, have acceptable thermal expansion, and resist excessive deformation due to the hydrogen pressure generated by the fuel. The fuel cladding material which was selected is a nickel-base alloy, Hastelloy N, in the form of tubes internally coated with a ceramic hydrogen permeation barrier.

During fabrication of the cladding tubes, the metallurgical condition of the Hastelloy N is changed from the as-received tube stock by several processes during the application of the ceramic coating. Prior to ceramic coating, the cladding tubes are subjected to a chromizing process which introduces a chromium-rich surface on both the inner and outer surfaces of the tube. After coating with a ceramic slip, the tubes are fired at a high temperature to fuse the ceramic. This firing cycle causes grain growth in the Hastelloy N and results in large-grained material.

The operating environment of the fuel element cladding is complex and consists of hydrogen permeating through the tube wall, NaK flowing around the outer surface at 1300°F, a longitudinal thermal gradient of 200°F, and the associated reactor neutron flux.*

These processing and operating parameters are an integral part of the SNAP reactors, and their effect upon the mechanical properties of Hastelloy N must be determined to accurately predict the performance of the fuel element cladding. The purpose of this study was to evaluate the effects of these parameters (excluding neutron irradiation) upon the creep properties of Hastelloy N under simulated SNAP operating conditions. Creep tests of 1,000-hr duration were performed with the processing and operating parameters as test inputs.

*SNAP 8, 600 kw thermal operating conditions

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Figure 1. Typical Assembled Cladding Creep Test Sample with Longitudinal Cross Section

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II. EXPERIMENTAL

A. SAMPLE PREPARATION

The samples used in this creep testing program, as shown in Figure 1, were shortened SNAP 8 cladding tubes, fitted with end caps and pressure probes so that they could be pressurized internally. When pressurized, this configuration produces a biaxial stress condition on the material. Although biaxial stresses are more difficult to analyze, they simulate the conditions under which the cladding exists in reactor service. The sample tubes were prepared from 0.560-in. OD by 0.010-in. wall seamless Hastelloy N tubing which had been fabricated to SNAP 8 specifications. The chemical analysis and average room-temperature tensile properties of this heat are listed in Table 1.

TABLE 1
CHEMICAL COMPOSITION AND ROOM TEMPERATURE
TENSILE PROPERTIES OF HASTELLOY N, HEAT
NUMBER Y8437

Chemical Analysis (wt %)			
Ni - 74.17	Mo - 15.85	Cr - 6.53	Fe - 2.53
Ti - 0.40	Mn - 0.30	C - 0.07	Si - 0.11
Co - 0.01	O - 0.0094	S - 0.007	N - 0.0028
H - 0.0017	—	—	—
Tensile Properties (SNAP 8 tubing specimens)			
0.2% Offset Yield Strength (psi)	Ultimate Tensile Strength (psi)	Elongation in 2.00 in. (%)	
65,000	140,600	43	

Fabrication processes involved in producing SNAP cladding tubes are as follows: the tubing is first cut into suitable lengths and the blind-end cap is butt-welded to the tube. This assembly is then pack-chromized, vacuum-annealed, and straightened. The internal surfaces of the tube assembly are then coated with a ceramic slip and fired to fuse the ceramic material. Test specimens were obtained at this point.

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a. Typical AI-SCB Coated,
Large Grained Material
(ASTM grain size
3.5 to 4.5)

5306-2-1

b. Typical AI-8763D Coated,
Small Grained Material
(ASTM grain size
6.5 to 7.5)

5671-2-1

Figure 2. Coated Chromized Hastelloy N

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The tubes were cut to 9-in. lengths and 1/4 in. of ceramic was removed from the open end. Initially, this ceramic was removed on a lathe, but this procedure proved to be unsatisfactory because it removed metal from a region which is highly stressed during the test and caused premature ruptures. In the preparation of later samples, the ceramic was removed by liquid honing* which satisfactorily removed the ceramic. An end cap, designed to accommodate a 3/16-in. stainless steel capillary pressure probe for supplying internal pressure to the tubes, was then welded to the open end of the tube. Specimens used in the early part of the program were welded on the production S8ER fuel element assembly TIG welder, while later specimens were electron-beam welded when this procedure was adopted for S8DS production.

This assembly was helium-leak checked and pressure tested at room temperature, with an internal pressure of 400 psig. The surface was cleaned of oxides by liquid honing in preparation for diametral measurements. Reference marks were scribed on the face of each end cap, and the outside diameter profile was obtained by making two measurements 90° apart, at 1/2-in. increments along the length of the tube. A high precision Super-micrometer (± 0.0002 in.) was used for these measurements. An identical procedure using the same reference marks was used to obtain the post-test diametral profile. These measurements are the basis for the results obtained during this investigation.

Two types of ceramic hydrogen barrier coatings have been used in SNAP 8 fuel elements. To determine the effect of these coatings upon the creep properties of the cladding, several tubes were removed from production before application of the coating. These tubes were subjected to identical coating firing cycles as the coated tubes. The AI-8763D coating process consists of three firing cycles of 15 min each, at 1950°F. The SCB coating process consists of two firing cycles of 5 min each, at 2100°F. The major difference, with respect to the mechanical properties of Hastelloy N of these coatings, is the grain size that results from the firing cycles. The SCB firing cycle produces larger grained material (ASTM 3.5 to 4.5) than the AI-8763D firing cycles (ASTM 6.5 to 7.5). Typical photomicrographs of transverse sections of chromized Hastelloy N tubes coated with AI-8763D and SCB ceramic coatings are compared in Figure 2.

*A sand-water mixture accelerated by air pressure

B. PARAMETERS TESTED

As previously mentioned, the processing and operating parameters for SNAP 8 reactor fuel element cladding are complex. Creep tests were performed to evaluate the effects of these parameters upon the creep performance of chromized Hastelloy N. A summary of the parameters studied are as follows:

- 1) The effects of an external environment of flowing NaK-78* were determined by creep testing SNAP 8 cladding tubes in a NaK thermal convection loop, and then duplicating the test in a vacuum.
- 2) The effects of hydrogen on creep were determined by internally pressurizing the cladding tubes with hydrogen, and duplicating the test with argon as the pressurizing gas.
- 3) The relative effects of the ceramic coatings (SCB, AI-8763D) on creep were determined by testing cladding tubes coated with SCB and AI-8763D ceramic under identical test conditions.
- 4) The general effect of ceramic coatings on creep was determined by testing coated and uncoated cladding tubes under identical conditions. The uncoated tubes were subjected to the same firing cycles as coated tubes.
- 5) The effect of high-hydrogen permeation rates through the cladding on creep was determined by testing coated and uncoated cladding tubes internally pressurized with hydrogen.
- 6) The effect of grain size on creep was determined by comparing data obtained in Items 2, 3, 4, and 5.
- 7) The effect of stress on creep for all parameters tested was studied by producing hoop stresses of 12,000, 8,000, 5,000, 4,000, and 2,500 psi.

C. TESTING EQUIPMENT AND PROCEDURES

To provide external environments of vacuum or NaK for creep testing of SNAP cladding tubes, it was necessary to construct two separate testing systems. In both systems, a tangential stress was produced in the samples by internal pressurization.

*Eutectic sodium-potassium alloy

1. Vacuum Creep Testing

The equipment used for creep testing in vacuum is illustrated in Figure 3. Five cladding tubes were placed in each of the two Inconel retorts through a removable flange. The pressure probes extended through the flange and were sealed by O-ring pressure fittings. Stainless steel grid plates were used to space the specimens within the cluster in the retort. Temperatures were monitored on a multipoint recorder by thermocouples which passed through the flange and were sealed by Conax fittings. Resistance-type furnaces surrounded the retorts, and adjustments were made to provide an isothermal zone for the test specimens. Temperature control was provided by on-off-type controllers. The system was protected from temperature excursions by overtemperature controls.

A dynamic vacuum (10μ) was maintained in the retort with a mechanical roughing pump. The cladding tubes were kept free of oxide by inserting zirconium foil as a getter in the heated zone of the retorts. A dynamic pressure of either argon or hydrogen was maintained inside the cladding tubes by a pressurizing system. This system consisted of a gas supply bottle, a ballast tank, a pressure regulator and a distribution manifold. The ballast supplied pressure to the tubes and was a safety feature in that if a tube ruptured, only the small ballast tank would be emptied into the vacuum system. The pressure regulator was used to maintain the desired pressure level in the cladding tubes. The distribution manifold contained valves for each cladding tube. In case of a tube rupture, the tube could be isolated without interrupting the test. The pressures in each manifold were monitored by a 0- to 500-psi strain-gauge pressure transducer. The output from the transducers were plotted on the multipoint recorder, and when a tube ruptured, the time at which the rupture occurred was recorded.

The furnaces were brought to temperature (1400°F), and allowed to stabilize. Adjustments were made to ensure an isothermal zone over the test specimens. When the system was operating satisfactorily, the creep test was initiated by internally pressurizing the cladding tubes to the desired stress level.

The principal stress in the material of an internally pressurized thin wall tube is the hoop stress. This stress is defined by the following equation:

$$\sigma_H = \frac{PD}{2t} \quad \dots (1)$$

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Figure 3. Testing System for Creep Tests Conducted in a Vacuum
(Figure Unclassified)

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where

σ_H = hoop stress

P = internal pressure

D = mean diameter of tube

t = wall thickness.

Stresses used for these tests were 12,000, 8,000, 5,000, 4,000, and 2,500 psi. The diametrical deformation was obtained by comparing the post-test measurements with the pre-test measurements, and the creep rate was calculated by using the amount of deformation and the test time.

2. NaK Creep Testing

A series of creep tests similar to the tests performed in vacuum were conducted with NaK-78 as the external environment. The NaK duplicates the reactor heat transfer medium and the tests were performed to determine its effect upon the creep characteristics of the cladding.

A schematic of a typical thermal convection loop used for the cladding creep experiments is shown in Figure 4. The loops were constructed from 1-in.-diameter, Schedule 40, AISI Type 316 stainless steel pipe. Calrod heaters were

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Figure 4. Schematic of Liquid Metal Thermal Convection Loop for Creep Test Conducted in NaK (Figure Unclassified)

attached to the outside of the hot leg just below the sample. The entire system was insulated and the bottom of the cold leg was continuously cold trapped at about 125°F. The test specimens were identical to those used in the vacuum creep tests and each loop contained only one specimen. Immersion-type thermocouples were placed above and below the test specimen and indicated a 10°F longitudinal temperature gradient over the length of the test specimen. The temperature drop across the loop was ~100°F.

The specimens were internally pressurized in the same manner as those in

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the vacuum tests. Startup and operation procedures were also similar to the vacuum tests. Test initiation by pressurizing the tubes was not started until the system was operating satisfactorily and the tubes were depressurized in case of a power failure. At the end of the test period (1,000 hr), the loops were drained and the test specimens were removed. Creep rates were obtained in the same manner as for the vacuum tests.

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III. RESULTS AND DISCUSSION

The results of this study are presented in Tables 2, 3, 4, 5, and 6. These tables show the data obtained for all parameters tested at specific stress levels. These data were compared with uniaxial data reported for INOR-8 (Hastelloy N) in air and molten salt.^(1,8) The uniaxial INOR-8 data were normalized to hoop stress and diametral creep rate by the Von Mises and the Solderberg-modified Von Mises criterions, respectively (see Appendix). Comparisons of the present work with the INOR-8 data⁽¹⁾ is shown in graphic form in Figures 5, 6, and 7. Figure 5 shows all the data collected and the range of deviations experienced due to the parameters tested. All tests were intended to be at 1400°F, but a few tests were slightly off temperature ($\pm 20^\circ\text{F}$) and were corrected to 1400°F. The temperature correction factors were obtained from INOR-8 test data, which covered the range of temperatures.

A. VACUUM CREEP TESTS

All data obtained in vacuum are contained in Figures 6 and 7. Figure 6 shows the effects of hydrogen on large and small grained uncoated tubes, while Figure 7 shows these effects on coated tubes. The data obtained using argon as the pressurizing gas on uncoated tubes generally follows the INOR-8 data for all stresses tested. When hydrogen was used, the small grained tubes exhibited accelerated creep at the low stress levels but, at the high stress levels, the departure from INOR-8 data was not significant.

Coated tubes (Figure 7) generally had higher creep rates than the uncoated tubes for both argon and hydrogen and there appears to be little effect of hydrogen relative to argon. The accelerated creep at low stress levels is also noted for the coated tubes; however, the effects of grain size are not as noticeable.

From an overall viewpoint, these effects noted for the vacuum tests are not pronounced, but may be considered as trends for long-term considerations. Creep acceleration at low stresses has also been noted by Engberg.⁽²⁾ Fuel elements which were operated at 1400°F and ~1,250 psi hoop stress for 10,000 hr were used in his investigation. The accuracy of the low-stress creep data obtained to date may be questionable due to the small deformations obtained; however, the apparent reduction in creep resistance is significant and should not be ignored.

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TABLE 2
CLADDING CREEP TEST - 12,000 psi, 1400°F

Environment		Coating	ASTM Grain Size	Average Diametrical Deformation (%)	Average Diametrical Creep Rate (%/hr)	Time to Rupture (hr)
Internal	External					
Hydrogen	Vacuum	AI-SCB	4 - 4.5	4.38	13.6×10^{-3}	322
Hydrogen	Vacuum	AI-SCB	4 - 4.5	3.39	11.3×10^{-3}	300
Argon	Vacuum	AI-SCB	3.5 - 4	4.04	4.82×10^{-3}	838
Argon	Vacuum	AI-SCB	4 - 4.5	3.65	6.63×10^{-3}	550
Hydrogen	Vacuum	AI-8763D	6.5 - 7.5	0.57	8.3×10^{-3}	68*
Argon	Vacuum	AI-8763D	6.5 - 7.5	0.98	2.53×10^{-3}	390*
Hydrogen	Vacuum	None - AI-SCB Firing Cycle	3.5 - 4	3.88	4.93×10^{-3}	786
Argon	Vacuum	None - AI-SCB Firing Cycle	4 - 4.5	1.62	3.39×10^{-3}	477*
Hydrogen	Vacuum	None - AI-8763D Firing Cycle	6.5 - 7.5	3.45	6.30×10^{-3}	547
Argon	Vacuum	None - AI-8763D Firing Cycle	6.5 - 7.5	1.60	4.10×10^{-3}	390*

*These samples ruptured prematurely, due to weld defects

TABLE 3
CLADDING CREEP TEST - 8,000 psi, 1400°F, 1,000 hr

Environment		Coating	ASTM Grain Size	Average Diametrical Deformation (%)	Average Diametrical Creep Rate (%/hr)
Internal	External				
Hydrogen	Vacuum	AI-SCB	4 - 4.5	0.56	5.65×10^{-4}
Hydrogen	Vacuum	AI-SCB	4 - 4.5	0.67	6.69×10^{-4}
Argon	Vacuum	AI-SCB	4 - 4.5	0.90	9.03×10^{-4}
Argon	Vacuum	AI-SCB	4 - 4.5	0.51	5.19×10^{-4}
Hydrogen	Vacuum	AI-8763D	6.5 - 7.5	0.53	5.35×10^{-4}
Argon	Vacuum	AI-8763D	6.5 - 7.5	0.57	5.72×10^{-4}
Hydrogen	Vacuum	None - AI-SCB Firing Cycle	4 - 4.5	0.44	4.46×10^{-4}
Argon	Vacuum	None - AI-SCB Firing Cycle	4 - 4.5	0.30	3.00×10^{-4}
Hydrogen	Vacuum	None - AI-8763D Firing Cycle	6.5 - 7.5	0.58	5.81×10^{-4}
Argon	Vacuum	None - AI-8763D Firing Cycle	6.5 - 7.5	0.53	5.39×10^{-4}

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TABLE 4
CLADDING CREEP TEST - 5,000 psi, 1400°F, 1,000 hr

Environment		Coating	ASTM Grain Size	Average Diametrical Deformation (%)	Average Diametrical Creep Rate (%/hr)
Internal	External				
Hydrogen	NaK	Al-8763D	6.5 - 7.5	0.40	4.07×10^{-4}
Hydrogen	NaK	Al-8763D	6.5 - 7.5	0.43	4.37×10^{-4}
Argon	NaK	Al-8763D	6.5 - 7.5	0.34	3.45×10^{-4}
Hydrogen	Vacuum	Al-8763D	6.5 - 7.5	0.33	3.3×10^{-4}
Argon	Vacuum	Al-8763D	6.5 - 7.5	0.28	2.8×10^{-4}

TABLE 5
CLADDING CREEP TEST - 4,000 psi, 1400°F, 1,000 hr

Environment		Coating	ASTM Grain Size	Average Diametrical Deformation (%)	Average Diametrical Creep Rate (%/hr)
Internal	External				
Hydrogen	Vacuum	Al-SCB	4.5 - 5	0.02	2.1×10^{-5}
Hydrogen	Vacuum	Al-SCB	4.5 - 5	0.04	4.2×10^{-5}
Argon	Vacuum	Al-SCB	4.5 - 5	0.11	11.1×10^{-5}
Argon	Vacuum	Al-SCB	4.5 - 5	0.06	6.9×10^{-5}
Hydrogen	Vacuum	Al-8763D	6.5 - 7.5	0.18	18.0×10^{-5}
Argon	Vacuum	Al-8763D	6.5 - 7.5	0.20	20.0×10^{-5}
Hydrogen	Vacuum	None - Al-SCB Firing Cycle	4 - 4.5	0.01	1.0×10^{-5}
Argon	Vacuum	None - Al-SCB Firing Cycle	4.5 - 5	0.05	5.1×10^{-5}
Hydrogen	Vacuum	None - Al-8763D Firing Cycle	6.5 - 7.5	0.11	11.9×10^{-5}
Argon	Vacuum	None - Al-8763D Firing Cycle	6.5 - 7.5	0.08	8.8×10^{-5}

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TABLE 6
CLADDING CREEP TEST - 2,500 psi, 1400°F, 1,000 hr

Environment		Coating	ASTM Grain Size	Average Diametrical Deformation (%)	Average Diametrical Creep Rate (%/hr)
Internal	External				
Hydrogen	Vacuum	AI-SCB	2 - 4	0.060	6.2×10^{-5}
Argon	Vacuum	AI-SCB	2 - 4	0.049	4.9×10^{-5}
Hydrogen	Vacuum	AI-8763D	5 - 7	0.100	11.0×10^{-5}
Hydrogen	Vacuum	AI-8763D	5 - 7	0.080	8.1×10^{-5}
Argon	Vacuum	AI-8763D	5 - 7	0.048	4.8×10^{-5}
Argon	Vacuum	AI-8763D	5 - 7	0.110	11.1×10^{-5}
Hydrogen	Vacuum	None - AI-SCB Firing Cycle	2 - 4	No measurable increase	-
Argon	Vacuum	None - AI-SCB Firing Cycle	2 - 4	0.003	0.3×10^{-5}
Hydrogen	Vacuum	None - AI-8763D Firing Cycle	5 - 7	0.14	11.45×10^{-5}
Argon	Vacuum	None - AI-8763D Firing Cycle	5 - 7	0.003	0.35×10^{-5}

All of the samples in the 12,000 psi hoop stress series failed prior to 1,000 hr, as shown in Table 2. Several of the tubes prematurely failed in the end cap weld area due to a thinning of the wall, but the creep data are still valid. The data presented in Figure 8 are for SCB-coated tubes, and indicate that deformation to a normal creep failure at 1400°F is ~4%. Also noted is that hydrogen as a pressurizing gas caused slightly earlier failures than when argon was used. Figure 9a shows the appearance of a normal cladding creep failure area. This failure was produced by the hoop stress in the tube, and its length is parallel to the longitudinal axis of the tube. A microscopic section (Figure 9b) of this failure shows the typical intergranular creep failure. The grains are not deformed, and other areas of intergranular separation can be seen. The creep phenomenon is characterized by low deformations and intergranular separation, whereas tube burst specimens (short-term) undergo large deformations (30 to 40%) and fail transgranularly.

B. CREEP TESTS CONDUCTED IN NaK-78

The results of the biaxial creep tests conducted with an external environment of flowing NaK are listed in Table 4. Also included are results from comparable

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Figure 5. Cladding Creep Data Obtained for SNAP 8 Reactor Parameters Compared with Normalized INOR-8 Data (Figure Unclassified)

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Figure 6. Effects of Internal Environment and Grain Size on the Creep Properties of Uncoated SNAP Fuel Element Cladding (Figure Unclassified)

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Figure 7. Effects of Internal Environment and Coatings on the Creep Properties of Coated SNAP Fuel Element Cladding (Figure Unclassified)

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Figure 8. Effect of Internal Environment on Time to Rupture (Figure Unclassified)

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a. Showing Longitudinal
Creep Rupture

5572-10-1

b. Transverse Section
Showing Intergranular
Creep Failure

Figure 9. Typical Creep
Rupture Produced by Tan-
gential Stresses (Ceramic
hydrogen barrier was in-
advertently removed dur-
ing mounting)
(Figure Unclassified)

5572-10-1

Figure 10. Transverse
Section of Cladding Tube
Exposed to Flowing NaK
at 1400°F for 1,000 hr

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5646-1-7

a. Longitudinal Section Showing Corrosion of Hastelloy N

5646-1-2

b. Rupture Area Showing Corrosion of Hastelloy N

Figure 11. Corrosion Effects Resulting From a Ruptured Cladding Tube Tested in NaKat 1400°F (Figure Unclassified)

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tests conducted in vacuum. As indicated in the table, these tests were conducted at 5,000 psi hoop stress and 1400°F on AI-8763D coated tubes.

In general, the NaK environment seemed to accelerate the creep rate slightly as compared to creep rates obtained in vacuum. The presence of hydrogen also seemed to accelerate the creep rate somewhat.

As added information, it was noted that the chromized Hastelloy N exhibited excellent resistance to NaK corrosion. A photomicrograph (Figure 10) of a transverse section of a test sample exposed to flowing NaK at 1400°F for 1,000 hr verifies the resistance to NaK corrosion.

In this and earlier creep tests⁽³⁾ conducted in flowing NaK, two unexpected creep ruptures occurred. One tube was internally pressurized with argon, while the other was internally pressurized with hydrogen. Failure analysis of the argon-pressurized tube revealed a thinned wall section at the rupture point. This thinning caused higher stresses than expected and, consequently, premature failure.

Failure analysis of the hydrogen-pressurized tube indicated the rupture occurred near the end cap closure weld. This premature failure was attributed to the use of an experimental welding technique being developed for SNAP 8 cladding closure welds. Welding techniques have now been perfected to eliminate this problem, and this type of failure is not expected in reactor service.

The sample failures observed in the NaK tests occurred less than 1 in. from the end of the tube. Since a complex multiaxial stress due to end effects exists at this point, the failure was not a typical biaxial creep failure, as evidenced by the circumferential, rather than longitudinal, rupture. Both failures were intergranular in nature.

Although creep safety factors incorporated in the SNAP reactor fuel elements should insure the integrity of the cladding tube during operation, it is worthwhile mentioning the post-rupture developments observed in the higher stress accelerated NaK creep tests.

A cross section through the ruptured area of the hydrogen pressurized tube is presented in Figure 11a. The rupture occurred adjacent to the weld area through which NaK seeped to the inside and reacted with the ceramic coating. The products of this reaction appear to be highly corrosive to Hastelloy N, as noted by the

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removal of cladding material on both the inside and outside surfaces of the tube. A photomacrograph of the NaK side of the rupture area showing the corrosion on the outer surface is presented in Figure 11b. After removing the ruptured tube from the NaK loop, a light buildup of foreign material covered the NaK side of the rupture area. Similar post-rupture reactions were noted in the argon-pressurized tube.

The effect of radiation on the creep rate of Hastelloy N was not included in this study. Creep tests performed on various other alloys during irradiation indicate that the creep rate is generally decreased due to radiation.⁽⁵⁾

Creep tests performed on various other alloys during irradiation indicate that the rupture ductility is generally decreased due to radiation.⁽⁵⁾

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IV. CONCLUSIONS

These creep tests on SNAP 8 reactor fuel element cladding can be summarized with the following conclusions:

1) The various processing and operating parameters (excluding radiation) cause no gross changes in the creep properties of the SNAP reactor fuel element cladding material.

2) At high stress levels ($>4,000$ psi hoop stress), trends are detectable for various parameters, and these trends become more noticeable at lower stresses.

3) When comparing the low-stress data with an extrapolation of higher stress data, the creep rate appears to be accelerated for certain parameters. The coated tubes had accelerated creep rates, and the most accelerated condition was caused by hydrogen permeating through small-grained cladding tubes.

It is important to remember that these tests were conducted for only 1,000 hr and that the observed trends could be significant for long-term considerations.

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APPENDIX

CORRELATION BETWEEN UNIAXIAL AND BIAXIAL CREEP DATA

Since it is important to know whether the SNAP processing and operating parameters examined in this study have any effect on the creep behavior of Hastelloy N, these data were compared with those reported in literature.^(1,8) The literature data are generally for uniaxial tests, and the internally pressurized tubes used in this study were in a biaxially stressed condition. It was, therefore, necessary to establish a method of correlating uniaxial and biaxial data. Several investigators^(6,7) have found that the most accurate method of correlating uniaxial and biaxial creep data is based on the Von Mises criterion for yielding.

The general equation for the effective stress ($\bar{\sigma}$) in a test specimen is given by:

$$\bar{\sigma} = \frac{1}{\sqrt{2}} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \quad \dots (2)$$

where σ_1 , σ_2 , and σ_3 are the principal normal stresses in order of decreasing magnitude. In a uniaxially-stressed specimen, σ_2 and $\sigma_3 = 0$, and the effective stress ($\bar{\sigma}$) is the uniaxial stress (σ_1). In the biaxially stressed condition of the internally pressurized tube, the principal stresses are the hoop stress (σ_h) and the axial stress (σ_a), where $\sigma_a = \sigma_h/2$. Substitution of these values into the general equation gives the relationship between effective stress and the hoop stress of

$$\bar{\sigma} = \frac{\sqrt{3}}{2} \sigma_h = 0.866 \sigma_h \quad \dots (3)$$

The effective minimum creep rate ($\dot{\epsilon}$) is defined by the Solderberg-modified Von Mises criterion as:

$$\dot{\epsilon} = \frac{\sqrt{2}}{3} \sqrt{(\dot{\epsilon}_1 - \dot{\epsilon}_2)^2 + (\dot{\epsilon}_2 - \dot{\epsilon}_3)^2 + (\dot{\epsilon}_3 - \dot{\epsilon}_1)^2} \quad \dots (4)$$

where $\dot{\epsilon}_1$, $\dot{\epsilon}_2$, and $\dot{\epsilon}_3$ are the strain rates corresponding to the principal stresses σ_1 , σ_2 , and σ_3 . Incorporating Poisson's ratio into the calculation, the effective

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creep rate ($\dot{\epsilon}$) in the biaxial condition is $1.15 \dot{\epsilon}_d$, where $\dot{\epsilon}_d$ is the diametrical creep rate.

By using these correlations for stress and creep rate, uniaxial and biaxial data comparisons were made between literature values and the data obtained in these tests.

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