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BIAXIAL CREEP AND STRESS RUPTURE
OF
WIRE-WRAPPED CLADDING
IN
1200°F SODIUM UNDER ΔT CONDITIONS
INTERIM REPORT

AEC Research and Development Report

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By
J. H. SHIVELY

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ABSTRACT

The results of biaxial stress-rupture and creep data tests on 10 to 15% cold-worked Type 316 stainless steel are presented. The tests were performed at 1200°F, in sodium flowing at 6 ft/sec. A system ΔT of 50°F was induced, just ahead of the test section. The tubes were wrapped with 0.070-in. diameter stainless steel wires with a 12-in. pitch, arranged in a close-packed array and surrounded with a hexagonal stainless steel shroud tube. The purpose of the test was to study the mass transfer effects of flowing sodium, acting in concert with wire spacers, on the biaxial creep behavior of stainless steel cladding. Control tests without wires were made in static sodium.

The stress-rupture life of wire-wrapped tubes in flowing sodium falls within the uncertainty band for tests made in static sodium on another lot of larger diameter. Some failures were located under wires near the inlet, which may be explained by interactions of wires and cladding, introduced during attachment of the wires to the tube end caps. The observed wire shortening was related to tube diametral strain. Self-welding of wires to tubes was also observed. These results are only preliminary, pending further examination of the tubes.

I. INTRODUCTION

To predict the performance of fuel cladding in a Liquid Metal Cooled Fast Breeder Reactor (LMFBR) requires a thorough understanding of those factors in the environment which affect the integrity of the cladding. Because of the limited space available for in-pile testing, much of the design information about cladding and structural materials must be gained through testing under conditions which simulate the non-nuclear aspects of the environment. This includes stress, stress-state, heat flux, temperature, and the mass transport effects of flowing sodium. The primary emphasis of the Sodium Technology Program at Atomics International (AI) is to relate the quality of the sodium to the performance of fuel cladding under conditions which simulate the extremes of those found in LMFBR's (extremes, because the temperatures and pressures are higher).

As part of this program, biaxial stress-rupture and creep tests were made on cold-worked Type 316 stainless steel cladding, in flowing sodium, and under a loop ΔT . The cladding was wire wrapped. The purpose of the test was to study the combined effects of mass transfer from flowing sodium and wire wrap spacers on the mechanical behavior of the cladding. Suitable control tests were also made in static sodium, but without wires.

Figure 1. Schematic Diagram of 2-in. Loop

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II. EXPERIMENTAL

A. FLOWING SODIUM LOOP

The 2-in. flowing sodium loop is shown schematically in Figure 1. In order to accommodate the test assembly and to create the conditions which favor mass transfer, a ΔT leg was added to the loop. The leg is shown in Figure 2. The horizontal section is used to heat the flowing sodium prior to entering the vertical test section. The leg was designed to generate a 50°F ΔT in the sodium, just prior to entering the test column. The temperature at the inlet to the test column was fixed at 1200°F . Heat losses throughout the piping were sufficient to drop the temperature, prior to entering the heater section of the leg, to 1150°F . The conditions of the test are given in Table 1.

B. THE 19-PIN ASSEMBLY

The test assembly consists of 19 individually pressurized tubes of Type 316 stainless steel in the 10 to 15% cold-worked condition. The tubes are 20-in. long by 0.250-in. OD by 10-mil wall. The tubes were helically wrapped (12-in. pitch) with 70-mil wires of annealed Type 316 stainless steel. During assembly, the tubes were arranged in a hexagonal array, and a shroud tube was placed around them. A strain allowance of 8% $\Delta D/D$ was built into the array. The completed assembly, as shown in Figure 3, was placed in loop. Pertinent data about the assembly are presented in Table 2.

The pressure in the tubes was set to prescribed values, according to the desired hoop stress. The stresses were calculated, using the thin-walled tube formula:

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

where:

σ_H = hoop stress

D = inside diameter

P = pressure

t = thickness.

Figure 2. ΔT Leg Installed on 2-in. Sodium Loop

Figure 3. 19-Pin Test Assembly With Housing

TABLE 1
TEST CONDITIONS FOR ΔT LEG

Test Temperature ($^{\circ}\text{F}$)	1200
Sodium Velocity (ft/sec)	6
Leg ΔT ($^{\circ}\text{F}$)	50
Bulk Sodium Temperature ($^{\circ}\text{F}$)	1150
Oxygen Content (ppm)	5
Carbon Content (ppm)	12

TABLE 2
TEST ASSEMBLY INFORMATION

Cladding Material	10 to 15% Cold-Worked Type 316 Stainless Steel
Cladding Dimensions (in.)	0.250-in. OD by 0.010-in. wall by 20-in. long
Wire-Wrap Material	Annealed Type 316 Stainless Steel
Wire Diameter (in.)	0.070
Wire-Wrap Pitch (in.)	12
Wire-Wrap Tension (lb)	40
Strain Allowance in Bundle	8% $\Delta D/D$
Shroud Material	Annealed Type 316 Stainless steel
Pressurization Gas	Helium
Pellet Dimensions (in.)	0.220-in. OD by 0.5-in. long
Pellet Material	Annealed Type 316 Stainless Steel
Weight of a Pin (lb)	~ 1
End-Cap Weld Type	Electron Beam Lap
End-Cap Material	Annealed Type 316 Stainless Steel
End-Cap Type	Solid Plug

The pressure in the tubes was programmed to produce stress-to-rupture and creep data in a reasonable amount of time. In the stress-rupture test, the internal pressure was held constant until the tube failed. In the creep test, seven identical tubes were pressurized to the same level and held at constant pressure. At prescribed time intervals, the pressure in each tube was removed. This was repeated on all seven tubes, for times ranging from 100 to 2613 hr. After completion of the test, the diameter of each tube was measured to yield values of diametral strain as a function of time at pressure. The results from the seven tubes then comprise a composite creep curve. The test conditions for each tube in the array are given in Table 3, and their position in the array is shown in Figure 4.

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Figure 4. Test Configuration for the ΔT Leg Experiment, as Viewed from Sodium Inlet to the Assembly

TABLE 3
SUMMARY OF DATA AND TEST CONDITIONS ON TUBES IN
1200°F FLOWING SODIUM

Pin No.	Hoop Stress (psi)	Type of Test	Time at Pressure (hr)	Strain† (%)	Average Strain Rate (%/hr x 10 ³)
16	25,148	Stress Rupture	2290	2.5	1.1
15	25,148	Stress Rupture	2613*	3.6	1.4
14	25,148	Stress Rupture	2418	3.1	1.3
5	25,148	Stress Rupture	809§	0.6	-
3	25,148	Stress Rupture	2100	2.9	1.4
9	25,148	Stress Rupture	2369	3.2	1.4
10	25,148	Creep	1009§	1.0	DNA
2	25,148	Creep	2009	2.0	DNA
13	25,148	Creep	1391	0.8	DNA
20	25,148	Creep	885	0.6	DNA
12	25,148	Creep	500	0.4	DNA
11	25,148	Creep	306	0.4	DNA
25	25,148	Creep	100	0.2	DNA
18	27,939	Stress Rupture	1242	2.6	2.1
17	27,939	Stress Rupture	498§	0.7	-
6	27,939	Stress Rupture	1242	3.4	2.7
7	29,804	Stress Rupture	754	4.8	6.4
19	29,804	Stress Rupture	706	3.0	4.2
21	29,804	Stress Rupture	987	NA	-

*Test was ended before rupture

†Strain for stress-rupture specimens is rupture; strain for creep specimens is average strain along the tube

§Denotes suspected premature ruptures

DNA - Does not apply to creep test, because specimens did not fail

NA - Not available at time of compilation

III. SUMMARY OF RESULTS

A. MECHANICAL BEHAVIOR

The stress-rupture results from the Type 316 stainless steel tubes in flowing sodium lie within the range of results obtained in static sodium for tubes of the same heat, but drawn to different diameter. This is illustrated in Figure 5. The static and dynamic sodium data are presented in Tables 3 and 4, respectively. Tests in static sodium in the same lot of tubing (same diameter) without wires are not complete; but, at the highest stress level, the stress-rupture lives agree with those from the flowing sodium tests.

The strain at rupture of tests in flowing sodium is less than that in static sodium, as can be seen in a comparison of Tables 3 and 4 for similar stresses. This is also illustrated in Figure 6, where the strain at rupture is plotted as a function of the average strain rate (rupture strain divided by time to rupture). Necessarily, these results are for the two different lots of tubing.

B. WIRE AND TUBE OBSERVATIONS

All of the wires in the test became loose during the test. The tubes were shorter after testing. The degree of looseness and tube shrinkage was a function of time at pressure and the stress level, and hence, accumulated strain. The results of length measurements is provided in Table 5.

C. SELF-WELDING

Indication of very localized self-welding between tubes and wires was observed. Adhesion of loose wires to neighboring pins, and adhesion of wires to their own tubes, was seen. An example of each kind of weld is shown in Figures 7 and 8.

D. FAILURE LOCATION AND MORPHOLOGY

All failures were intergranular. Seven failures occurred within 1 in. of the end cap weld at the inlet, and directly under the wire on the tube. Two failures occurred where loose wires touched the surfaces of neighboring tubes. Three failures were not associated with wires, and were premature relative to all other ruptures (see Figure 6).

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Figure 5. Stress-Rupture Behavior of Two Lots of Type 316 Stainless Steel in the 10 to 15% Cold-Worked Condition During Exposure to Static and Flowing Sodium at 1200°F

TABLE 4
SUMMARY OF DATA AND TEST CONDITIONS ON 10 TO 15% COLD-
WORKED TYPE 316 STAINLESS STEEL TUBES IN
1200°F STATIC SODIUM

Retort No.	Hoop Stress	Type of Test	Tube Diameter (in.)	Time at Pressure (hr)	Rupture or Average Strain (%)	Average Strain Rate (%/hr x 10 ³)
102	22,000	Stress Rupture	0.295	6770	4.3	0.63
102	22,000	Stress Rupture	0.295	7152	5.8	0.81
102	22,000	Stress Rupture	0.295	7046	4.8	0.67
102	25,000	Stress Rupture	0.295	3412	6.7	2.0
102	25,000	Stress Rupture	0.295	3623	9.8	2.7
102	25,000	Stress Rupture	0.295	3396	5.1	1.5
102	30,000	Stress Rupture	0.295	752	7.0	9.2
102	30,000	Stress Rupture	0.295	790	6.3	8.0
102	35,000	Stress Rupture	0.295	105	5.5	52.4
109	27,000	Stress Rupture	0.295	1189	8.3	7.0
109	27,000	Stress Rupture	0.295	1354	8.7	6.4
109	27,000	Stress Rupture	0.295	1822	12.2	6.7
109	32,000	Stress Rupture	0.295	276	5.3	19.2
109	32,000	Stress Rupture	0.295	292	6.4	22.0
109	32,000	Stress Rupture	0.295	206	2.5	12.0
109	34,000	Stress Rupture	0.295	129	4.0	30.6
124	25,148	Creep	0.295	97	0.25	DNA
124	25,148	Creep	0.295	306	0.42	DNA
124	25,148	Creep	0.295	502	0.50	DNA
124	25,148	Creep	0.295	866	0.84	DNA
124	25,148	Creep	0.295	1433	1.3	DNA
124	25,148	Creep	0.295	1994	3.1	DNA
124	25,148	Stress Rupture	0.295	2474	9.1	3.6
124	25,148	Stress Rupture	0.295	2522	8.6	3.4
124	25,148	Stress Rupture	0.295	2266	8.2	3.6
124	29,804	Stress Rupture	0.295	489	4.9	10.0
124	29,804	Stress Rupture	0.295	489	5.7	11.6
124	29,804	Stress Rupture	0.295	513	7.4	14.4
125	25,148	Creep	0.250	100	NA	NA
125	25,148	Creep	0.250	300	NA	NA
125	25,148	Creep	0.250	500	NA	NA
125	25,148	Creep	0.250	885	NA	NA
125	25,148	Creep	0.250	1400	NA	NA
125	25,148	Creep	0.250	2000	NA	NA
125	25,148	Stress Rupture	0.250	NA	NA	NA
125	25,148	Stress Rupture	0.250	NA	NA	NA
125	25,148	Stress Rupture	0.250	NA	NA	NA
125	29,804	Stress Rupture	0.250	776	NA	NA
125	29,804	Stress Rupture	0.250	814	NA	NA
125	29,804	Stress Rupture	0.250	824	NA	NA

DNA - Does not apply to creep test

NA - Not available, because test is still underway

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Figure 6. Comparison of the Relation Between Rupture Strain and Average Strain Rate for Two Lots of Type 316 Stainless Steel at 1200°F

TABLE 5
SUMMARY OF TUBE LENGTH MEASUREMENTS
(POST-TEST)

Tube No.	Tube Lengths		Time Under Stress (hr)
	X (in.)	Y (in.)	
2	20.159	20.023	2009
3	20.152	20.019	2100
5	20.171	20.033	809
6	20.121	19.992	1242
7	20.115	19.991	754
9	20.150	20.010	2369
10	20.165	20.026	1009
11	20.155	20.021	306
12	20.169	20.025	500
13	20.164	20.019	1391
14	20.110	19.969	2418
15	20.141	20.007	2613
16	20.148	20.021	2290
17	20.156	20.023	498
18	20.139	19.999	1242
19	20.145	20.002	706
20	20.174	20.027	885
21	20.152	20.007	987
25	20.165	20.026	100
1	20.179	20.042	0
4	20.191	20.056	0
22	20.181	20.041	0
23	20.176	20.049	0
8	20.171	20.041	0

X = Shoulder-to-Shoulder Distance

Y = Weld-to-Weld Distance

0 = Untested tubes built with others

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Figure 7. Adhesion (Self-Weld) of Wire Wrap to Cladding (Pin No. 6)

8629-2-1

Figure 8. Adhesion (Self-Weld) of Loose Wire on Neighboring Pin to Cladding (Pin No. 15)

E. MASS TRANSFER

Surface replicas and metallographic examination revealed evidence of mass transfer. The replicas showed considerable surface polishing relative to the untested tubes, as shown in Figures 9 and 10. The microstructures showed the presence of a ferrite layer at the surface. This can be seen in Figure 11.

F. WIRE INTERACTION

Besides self-welding, evidence of wire-cladding interaction was observed after the wires were removed. Flat spots were observed near the end caps on the cladding and on the wires, on both tested and untested tubes, as shown in Figures 12 and 13, respectively. Seven of the failures were located near these flat spots (see Figure 12). The interaction was introduced by clamping forces used to hold the wires in place during the welding.

G. SHROUD TUBE

The shroud tube, made of annealed Type 316 stainless steel, did not observably distort during the test. There was no evidence of wire interaction with the shroud. Based on this, the strain allowance in the array, and the strain measurements on the tubes, there was no mutual interaction between the wires, tubes, and shroud in the region of failures under the wires during the test. There was mutual interaction in the center of the bundle between loose wires and the shroud or cladding. It is perhaps surprising that adhesion to the shroud was not detected.

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Figure 9. Electron Photomicrograph of the Surface Replica Taken
on a Tube Before Exposure to Flowing Sodium

226702

a. 4 in. From the Inlet

2257015

b. At the Outlet

Figure 10. Electron Photomicrograph of Surface Replicas Taken at Two Locations on a Tube Exposed to Flowing Sodium (Pin No. 7)

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Figure 11. Ferrite Layer on the Surface
of the Cladding at the Inlet to the
Assembly after 2600 hr of
Exposure to Flowing Sodium

a. Outlet

8638-9-2

b. Inlet

8638-9-1

Figure 12. Wire-Cladding Interaction After Testing to Rupture in Flowing Sodium (Pin No. 18)

a. Outlet

8638-5-2

b. Inlet

8638-5-1

Figure 13. Wire-Cladding Interaction Before Testing in Flowing Sodium (Pin No. 1)

IV. RESULTS AND DISCUSSION

A. MECHANICAL BEHAVIOR

It is possible to compare the results of the biaxial creep and stress-rupture tests in flowing sodium to those obtained in static sodium. Unfortunately, most of the base-line data in static sodium are for a different lot (same heat) of cladding, with a 0.295-in. OD and 10 mil wall. The tubing tested in flowing sodium was 0.250-in. OD and 10 mil wall. The smaller diameter was selected, because it was closer to the Fast Flux Test Facility (FFTF) reference diameter. The tubing was procured to the same specification for both lots (except diameter), and contained 10 to 15% cold work in the "as-received condition." It is possible that the two lots did not contain exactly the same degree of cold work. There is little difference in room-temperature short-term properties between these two lots.

A comparison of the results of stress-rupture tests in flowing (ΔT leg) sodium and those in static sodium is presented in Figure 5. As can be seen, the stress-rupture data and the associated statistical band for the wire-wrapped tubes tested in flowing sodium overlaps the data and band for unwrapped tubes in static sodium. Stress-rupture tests in static sodium on the same lot as used in this experiment are still in progress. Ruptures in static sodium for this lot were obtained at the highest stress level (Retort 125 in Table 4). At the same stress level, the time to failure in this retort agreed with the time to failure in flowing sodium, but not with time to failure in static sodium on the 0.295-in. OD tubing (Retort 124). From these data, the stress-rupture life of the 0.250-in. OD tubing is longer than that of the 0.295-in. OD tubing at the same hoop stress and at 1200°F. The exact reason is not known, but may be due to differences in the amount of cold work or a wall thickness - to - tube diameter effect.

The slope of the flowing sodium stress-rupture curve is steeper than that for the static sodium curve (Figure 5). The reason for this steeper slope is not known. There are several possibilities. A steeper slope could arise from the presence of more cold work in the 0.250-in. diameter tubing (flowing sodium) than in the 0.295-in. diameter tubing. Previous work, under another task of this project, has shown that the slope of the stress-rupture curve increases

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Figure 14. Comparison of Biaxial Creep and Stress-Rupture Behavior of Two Lots of Type 316 Stainless Steel in Static and Flowing Sodium at 1200°F

with the degree of cold work.⁽¹⁾ Another possibility is that mass transfer of carbon resulted in a weakening of the cladding. This effect has been observed in zirconium-gettered static sodium by Lee,⁽²⁾ and more recently by GE in flowing sodium.⁽³⁾ Still another possibility is that wire-cladding interactions, which occurred during wire attachment and/or during the test, reduced the life under stress. Further insight into these mechanisms must await completion of the control tests on the 0.250-in. OD lot, and further evaluation of the results.

The rupture ductility of the wire-wrapped tubes tested in flowing sodium is less than the rupture ductility exhibited by unwrapped tubes in static sodium. This can be seen by comparison of strain at failures for the two tests presented in Tables 3 and 4. It can also be seen in Figure 6, in which the strain at rupture is plotted versus the average strain rate. The average strain rate is simply the rupture strain divided by the time to failure. The flowing sodium data is displaced from the static sodium data, and lies below it. Again, these data are for two different lots of tubing.

The rupture strain data may provide additional insight into the stress-rupture mechanisms. The lower rupture strain for the smaller diameter lot of tubing is commensurate with the presence of more cold work in the tubing.⁽¹⁾ Unfortunately, it is also compatible with the decarburization mechanism⁽²⁾ and the wire interaction mechanism (if any) mentioned earlier.

It should be mentioned that the average strain rate is not an accurate prediction of the secondary creep rate in cold-worked stainless steel. This can be seen in Figure 14, which portrays the composite biaxial creep curves for the two lots of stainless steel. As can be seen, the tubes exhibited a large amount of third-stage creep. The average creep rate, represented by a line joining the origin to the rupture strain, clearly overestimates the secondary creep rate, by at least a factor of 5 in static sodium and a factor of 3 in flowing sodium. The creep data in flowing sodium, presented in Figure 14, are not identical to those in static sodium. At least part of this difference may be explained by the presence of slightly more cold work in the 0.250-in. OD tubes relative to the 0.295-in. OD tubes (i. e., slightly lower secondary creep rate and lower rupture strain). A biaxial creep test on the 0.250-in. OD tubing is currently underway at 1200°F in static sodium.

Figure 15. Loose Wire on Pin No. 21, After Removal From the Array

Premature failures were observed in three tubes, presumably due to undetected defects in cladding. These failures fell outside of the 2σ scatter bands in the stress-rupture curve for the 0.250-in. OD in flowing sodium (see Figure 5), but fell on the creep curve (see Figure 14). The defects may be located on the ID of the tubing. The strain to failure on these tubes was also less than that for companion specimens. In fact, they lie on the creep curve. If these failures are due to cladding defects, then defects constituted a more serious life-limiting factor than either flowing sodium or wire interactions.

In summary, the stress-rupture and creep behavior of wire-wrapped stainless steel tubing in flowing sodium is very similar to, but not identical with, the behavior in static sodium on unwrapped tubes. Part of the discrepancy in behavior may be explained by differences in the degree of cold work present in the two lots of tubing, both from the same heat, and wire interactions introduced during fabrication. Another possibility is that mass transfer effects from flowing sodium influenced the stress-rupture and creep behavior of the cladding. In addition, there may be a wall thickness - tube diameter effect. Further enlightenment must await completion of control tests on the same lot of tubing in static sodium.

B. WIRE AND TUBE OBSERVATIONS

The wires on all tubes tested in the 19-pin array in flowing sodium became slackened. The first evidence of this was seen when Pin No. 21 (corner) was removed from the array, with the shroud tube still in place. The force to remove this pin was ~ 6 lb. The weight of the pin outside the assembly was ~ 1 lb. After removal of the shroud tube from the array, the reason for this interference was revealed. Most of wires were loose, and no longer in contact with the tubes. This can be seen in Figure 15. A differential strain allowance of 8% (20 mils) per tube between the wire-wrapped tubes and the housing, or between the wire-wrapped tubes themselves, was built into the assembly. Most of the wires moved away from the tubes by more than this amount, which produced an interference between loose wires and the shroud or neighboring tubes. The loose wires may be explained by tube shrinkage during creep.

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Figure 16. Weld-to-Weld Distance on Δ T Leg Tubes as a Function of Time Under Stress for Three Stress Levels

Unfortunately, the length of the tubes was not measured accurately before the test. Previous work on short tubes of Type 304 stainless steel had failed to show evidence of length changes in the tubes. Therefore, it is only possible to compare the length of untested tubes with those tested in flowing sodium. The distance between the end cap welds, and between the shoulders on the weld preps, were used as an index. The results of the measurements are presented in Table 5. All tested tubes were shorter than the untested tubes.

The shortening is a function of time under stress and stress level. This is illustrated in Figure 16. Clearly, all tubes became shorter during the test. The length decrease versus diametral strain for the tubes tested is shown in Figure 17. Clearly, the degree of shortening is proportional to the creep strain, within the uncertainty in the length.

Tube shrinkage is believed to be largely due to mechanical anisotropy. For a perfectly isotropic material under a 2:1 stress state, the length of the tube should remain fixed. However, if the creep strength in the longitudinal direction is greater than in the hoop direction, this assertion is not valid. In fact, in this case, the tubes would shrink. Previous work on cold-worked Type 316 stainless steel under the 1:0, 2:1, and 1:1 stress state showed that the rupture time obeys the largest principal stress failure criterion. Tests on cold-worked Type 304 stainless steel exhibited a correlation with von Mises' distortion energy criteria for failure. Thus, the cold-worked Type 316 stainless steel does not exhibit isotropy with respect to failure. It seems likely that it also does not exhibit isotropy with respect to creep strain.

The shortening of tubes can completely explain the looseness of wires in the 19-tube test. A length decrease of 20 mils (0.1%) produces a situation in which the wires appear longer. Since the ends of the wires are fixed, the wires bow outward, away from the cladding. The amount of deflection can be calculated by assuming the tube is a line cutting through an obtuse angle formed by the wire at the midpoint. The distance between the wire and the tube can be calculated by the following formula:

$$h \cong \sqrt{2L\Delta L} , \quad \dots(2)$$

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Figure 17. Tube Length as a Function of Diametral Strain

where:

h = height of wire above cladding

L = length of tube

ΔL = tube shrinkage.

Using 20 mils for ΔL , the distance between the wire and the tube is ~ 0.4 in. This value perhaps represents an upper limit. It exceeds by, a factor of 10, the space allowed between adjacent tubes.

In summary, wire loosening observed after the ΔT leg test is a result of tubes becoming shorter during creep deformation. Ideally, no tube shortening should occur for an isotropic material. From other data, it appears that cold-worked Type 316 stainless steel is anisotropic with respect to creep strength. This anisotropy can explain the small tube shrinkage, and thereby reconcile the wire slackening. The slackening is also a function of the particular state-of-stress (2:1) used for this test, and would not occur for a 1:1 stress state.

C. SELF-WELDING

Adhesion of wires to cladding was observed at two specific locations along the length of a tube: (1) at the ends of the tube, where the wire remains tightly compressed against the cladding, and (2) at the center of the tube, where a loose wire touched a neighboring tube. Near the ends of the tube, the adhesion remained intact after the test. A weld of this type is shown in Figure 7. After the wire was removed from the tube, the adhesion was essentially between high points on the surface. This suggests that the contact pressure was not very large. The contact was essentially along a line, as shown in Figure 18.

In contrast, the contact adhesions of loose wires to neighboring tubes were broken after the test. There is even evidence that these welds were formed and broken during this test. This is illustrated in Figures 7 and 19. As can be seen in the figures, small nuggets were removed from the wire and deposited on the cladding. In one case, the welding appeared to progress along the tube as the wire became looser. The size of the adhered deposit increased progressively, indicating that the force producing the adhesion increased with time. This is understandable, because the wire-cladding interference increases with creep strain (tube shrinkage).

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a. Outlet

8638-3-1

b. Inlet

Figure 18. Self-Weld Between Wire and Cladding
After Removal of Wire (Pin No. 14)

a. Cladding
(Pin No. 6)

b. Wire
(Pin No. 7)

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Figure 19. Self-Weld Areas of Cladding and Wire From a
Neighboring Pin

Figure 20. Interaction Between the Wire on Pin No. 7 and the Cladding in Pin No. 21 in the Region of the Failure

In summary, 15 instances of adhesion between wires and tubes were observed. In most of the cases, the welds were between surface asperities on wires and their own tubes. These welds suggest low contact pressures operated between the wires and tubes. In three cases, loose wires adhered to neighboring pins, depositing nuggets on the surface of the cladding and removing small chunks of wire material. These welds occurred progressively during the test, and may have involved larger contact forces than those directly under the wires.

D. FAILURE LOCATION AND WIRE INTERACTION

Failures were observed in 12 of the 19 tubes tested. Actually, one creep specimen not programmed for failure did rupture prematurely, and one stress-rupture specimen did not fail before the test was terminated after 2613 hr. The locations of all failures have been determined. Seven cladding failures occurred near the inlet to the bundle, within 1 in. of the end cap weld, and very near the end cap plug (see Figure 12). Two failures occurred near the middle of the bundle. There was evidence of a loose wire interaction with the cladding at the site of this failure (see Figure 20). Three of the failures were not associated with wires in any way. These failures were all premature, and are believed to be due to undetected cladding defects.

The failures under wires are probably associated with wire-cladding interactions, produced during the wire-wrapping process. A flat spot on the cladding and wire was observed near the end cap weld. This is shown in Figures 12 and 13 for tested and untested pins, respectively. A triangular zone of interaction on the surface of the cladding and on the surface of the wire results from the clamping force used to hold the wires in place on the tubes during welding of the wire to the end cap. The zone is triangular, because the end cap plug is tapered.

The seven failures which occurred under wires were located just behind these zones of interaction. The failure extended into the zone in some cases. It is not clearly evident that the failures were initiated by the present interaction zone. The failures may be associated with another wire interaction, not evident in the figures. The failure region was one major region of self-welding of the wires to the cladding (see Figure 8). The analysis of the causes for the locations of failures is therefore preliminary and inconclusive. An important

point, worth mentioning, is that undetected cladding defects had a stronger impact on rupture life and ductility than the wire-tube interactions produced during fabrication. In fact, it remains to be proven that either the wires or the flowing sodium produced any effect on mechanical behavior. This information must await completion of the control tests in static sodium on the same lot of tubing.

In summary, seven failures were found under wires. The presence of a cladding-wire interaction was detected on both tested and untested tubes. The interaction was introduced by clamping forces during attachment of the wire to the cladding tube end-caps. The effect of the interaction is unknown.

E. MASS TRANSFER

Surface replication of tubes exposed to flowing sodium has been used successfully to observe the effects of mass transfer. Replicas were made of the surfaces of tubes tested in flowing sodium in the ΔT leg. The appearances of the surfaces, before and after exposure, are presented in Figures 9 and 10, respectively. The extent of mass transfer cannot be determined from these replicas. Comparison of the surfaces from tests in flowing sodium under high heat flux to the surface shown in Figure 10 suggests that less corrosion has taken place. This is not surprising, because the surface temperature of the cladding is 50°F higher, and because of the lower velocity in the ΔT leg (20 ft/sec vs 6 ft/sec).

In addition, the driving force for corrosion provided by the undersaturation of the sodium with the corroding species is less, in the ΔT leg, than in the heater test. The smaller amount of undersaturation is a result of preheating the sodium in the ΔT leg, prior to its entrance to the test column. During the preheating, the surfaces of Type 304 stainless steel preheaters experience selective removal of the corroding species in the stainless steel. This reduces the degree of undersaturation, and hence the driving force for mass transfer.

Preliminary metallographic studies have revealed the presence of a ferrite layer on the surface of the cladding exposed to flowing sodium. No ferrite layer was observed in regions shadowed by the wires. The presence of a ferrite layer (Figure 11) is indicative of selective removal of chromium and nickel from the surface of the steel. The metastable austenite then transforms to ferrite.

The mass transfer is not the same at all locations on the surfaces of the tubes tested in flowing sodium. As expected, the surface polishing is less at the outlet to the assembly than at the inlet. This is a result of the corrosion along the bundle decreasing the driving force for mass transfer, by reducing the degree of undersaturation. In addition, the surfaces of the tubes shadowed by the wires do not exhibit strong evidence of mass transfer, providing confirmation of the velocity effect.⁽⁴⁾

Taken together, the metallography and surface impressions revealed evidence of mass transfer from the cladding. It is not known whether there was any migration of carbon, from or into the cladding.

V. CONCLUSIONS

Based on the initial observations mentioned previously, the following conclusions are drawn:

- 1) Comparison of the two lots of stainless steel tubing, one tested in flowing sodium and one tested in static sodium, suggests that there is essentially no change in the rupture life.
- 2) The tubes became shorter with increasing strain; the greater the total strain, the shorter the tubes became, and the greater the loosening of wires. The source of the tube shrinkage may be related to mechanical anisotropy in the steel. This is supported by the observation that Type 316 stainless steel does not obey von Mises' distortion energy criteria.
- 3) Sufficient force (pressure) was exerted between wires and cladding to produce adhesion of the wires to the tubes. The nature of the interaction was more pronounced in regions where loose wires and neighboring tubes touched than where wires were tight against their tubes, possibly due to surface changes from corrosion producing a diffusion potential.
- 4) Seven of twelve failures occurred under wires, and appear to be associated with the procedure used to attach the wires. The cause-effect relation for these failures is not completely understood.
- 5) Three of twelve failures were premature, were not under wires, and were probably linked to the presence of undetected defects in the cladding. The effect of the defects is more pronounced than either the effects of flowing sodium or wire-cladding interactions.
- 6) There is a difference in stress-rupture behavior in the two lots of cold-worked Type 316 stainless steel taken from the same heat. Both rupture life and the rupture ductility varied between the two lots.

- 7) Biaxial creep of cold-worked Type 316 stainless steel exhibits a larger amount of third-stage creep in static sodium than in flowing sodium. This may be due to differences in the two lots, to wire effects, or to mass transfer effects.
- 8) Evidence of mass transfer, found in the examination of tubes exposed to flowing sodium under a 50°F loop ΔT , was less than that observed in other tests under heat flux with a 50°F ΔT between the surface and inlet sodium temperatures.

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