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STAINLESS STEEL CLADDING DEVELOPMENT
QUARTERLY PROGRESS REPORT
FOR THE PERIOD ENDING MARCH 31, 1970

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U. S. Atomic Energy Commission

Submitted to AEC-NY00 in April 1970

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SECTION 1

INTRODUCTION

1. GENERAL

This is the seventh quarterly progress report and covers the work performed during the third quarter of FY-1970.

2. SUMMARY OF OBJECTIVES

This project is focused on the short term, and is concerned with steps to improve commercially available Type 316 austenitic stainless steels for use as cladding in LMFBR fuel pins. The overall project objective is to determine the influence of structure on mechanical properties of Type 316 austenitic stainless steel so that optimum specifications, which will assure maximum performance under LMFBR service conditions, can be selected.

The importance of structure on mechanical properties has been well demonstrated in the published literature. For example, in one series of experiments,^[1] prestraining of Type 316 austenitic stainless steel, followed by a specific heat treatment to produce carbide precipitation, decreased the minimum creep rate at temperatures of interest to LMFBR by as much as a factor of 250, and increased creep rupture life by as much as a factor of 25.

Initially in the cladding development program, a survey will be made to determine tubing material property and microstructural variability based on procurement of tubing under an existing FFTF specification. This specification will be used as a starting point. Materials with various fabrication histories will be procured and evaluated in both the as-fabricated condition and after post-fabrication heat treatment. The relations between mechanical properties and structure will be investigated.

It is anticipated that this first phase of the cladding program will culminate at the end of FY-1972 with a definition of the most desirable mechanical and microstructural properties in austenitic stainless steel, to maximize the strength and ductility of the material under the most limiting LMFBR service conditions.

3. SUMMARY OF PRIOR WORK

All work related to the present investigations and performed prior to the present period has been fully reported in:

WARD-3791-26, "Stainless Steel Cladding Development Quarterly Progress Report for the Period Ending September 30, 1968."

WARD-3791-29, "Stainless Steel Cladding Development Quarterly Progress Report for the Period Ending December 31, 1968."

WARD-3791-35, "Stainless Steel Cladding Development Quarterly Progress Report for the Period Ending March 31, 1969."

WARD-3791-41, "Stainless Steel Cladding Development Quarterly Progress Report for the Period Ending June 30, 1969."

WARD-4135-2, "Stainless Steel Cladding Development Quarterly Progress Report for the Period Ending September 30, 1969."

WARD-4135-5, "Stainless Steel Cladding Development Quarterly Progress Report for the Period Ending December 31, 1969."

4. SUMMARY OF CURRENT PROGRESS

Under Task SSBA-110, project administration and day-to-day liaison with the AEC/RDT continued. A preliminary meeting was held at AEC/RDT to discuss the plans for the FY-1971 program.

Under Task SSBA-210, microcharacterization and mechanical property testing, including biaxial tensile, biaxial stress rupture, and both uniaxial and biaxial creep were continued on WARD vacuum melted materials. Preliminary metallographic characterization of double vacuum melted Type 316 tubing, stainless steel fabricated by planetary swaging, has been completed for both 20 percent cold worked and solution annealed conditions.

Comprehensive structure characterization of the planetary swaged materials, including transmission and scanning electron microscopy, electron and X-ray diffraction, and texture analysis by pole figures, has been 75 percent completed.

Post test stress rupture specimens have been classified according to rupture type and microstructural evaluation of selected specimens initiated.

Biaxial stress rupture data scatter was evaluated, and a temperature correction procedure was proposed for the minor temperature variation ($\pm 15^{\circ}\text{F}$) inherent in the test.

Additional low cycle, high strain fatigue tests have been conducted. The new specimen design, testing procedure, and results from the current tests have been evaluated.

An additional partial shipment of 250 feet of 20 percent cold worked Battelle-Northwest double vacuum melted Type 316 stainless steel tubing has been received for use in the Oxide Fuel Element Development Program, bringing the total to 500 feet received to date. A shipment of 103 feet of solution annealed WARD double vacuum melted Type 316 stainless steel tubing, manufactured by planetary swaging, has been received for use in the characterization studies. Mechanical property testing and structural characterization have been initiated.

SECTION 2
SSBA-110 PROJECT ADMINISTRATION

F. A. Brassart, W. B. Heubel, and P. Murray

1. OBJECTIVES

The objectives of this task are to assure that the project is successfully completed, on schedule, within budget, and to the satisfaction of the Atomic Energy Commission (AEC); to assure compliance with contracted obligations; and to coordinate this project with other AEC-sponsored and Westinghouse-sponsored LMFBR development projects.

Overall project direction and day-to-day administration will be provided under this task. Plans and controls will be established and maintained, periodic reviews will be held with the AEC, correspondences and reports will be coordinated, and day-to-day technical and administrative liaison with the AEC will be provided.

2. CURRENT PROGRESS

Work programs for FY-1970 were submitted to the Commission in June 1969. Technical work has continued on the basis of those work programs. The project is divided into the following tasks for FY-1970 administrative control.

SSBA-110 Project Administration

SSBA-210 Evaluation of Austenitic Stainless Steel Cladding

SSBA-211 Effect of Cladding Properties and Interactions

A revised work program to cover SSBA-211 was submitted in December 1969. SSBA-211 was scheduled for completion in February 1970; however, at RDT's request, the scope of this task was increased. A final report for the task will be published in April 1970; no separate section of current progress is included in this report.

The quarterly progress report, WARD-4135-5, for the period ending December 31, 1969, was prepared and distributed.

SECTION 3

SSBA-210 EVALUATION OF AUSTENITIC STAINLESS STEEL CLADDING

M. G. Cowgill, T. R. Padden, W. E. Ray,
H. J. Snyder, K. C. Thomas, E. J. Tarby, and T. A. Galioto

1. OBJECTIVES

The objective of this task is to characterize in detail, by microstructural analysis, chemical analysis, and mechanical property testing, thin-wall stainless steel tubing fabricated under carefully controlled commercial practice. This information will be used to:

1. Enhance the understanding of the effect of fabrication processes and resulting structure on the properties of thin-wall tubing.
2. Provide out-of-reactor data required to predict and improve swelling behavior and strain limits of cladding in LMFBR environments.

The objective of a supplementary weldability investigation is to determine the effect of the degree of cold working on the weldability of Type 316 stainless steel tubing.

2. PRIOR WORK

A detailed test program was prepared. Air-melted, annealed Type 316 stainless steel tubing, 0.300-inch OD at three wall thicknesses (0.010, 0.012, and 0.014-inch), and 0.250-inch OD x 0.016-inch was procured. Extensive biaxial mechanical property testing at 850, 1000, 1200, and 1300°F, and chemical and microstructural evaluation of the tubing were performed.

Cold worked (15 to 20 percent), air melted tubing and micropeened air melted tubing were also procured. A study to determine the effects of micropeening on mechanical properties was performed, and an investigation of the effects of cold work was initiated.

All twelve lots of WARD vacuum melted tubing representing three melting practices, two grain sizes, and two conditions (20 percent cold worked and solution annealed) were received and accepted. Microcharacterization and mechanical property testing, including biaxial tensile, biaxial stress rupture, and both uniaxial and biaxial creep were initiated.

Chemical analysis and general metallographic characterization of the WARD vacuum melted tubing were completed.

Comprehensive structural characterization of two WARD double vacuum melted lots, including electron microscopy, and probe analysis as well as electron and X-ray diffraction analysis was completed.

A thermal aging study of several lots of Type 316 stainless steel was completed for times up to 5000 hours.

The experimental phase of an investigation of the effects of degree of cold work on weldability was completed; a summary is being prepared. A low cycle high strain fatigue study was initiated.

All ten lots of Battelle-Northwest Laboratories (BNW) double vacuum melted tubing for the Oxide Fuel Element Development Program (19-pin encapsulated assembly) were received and accepted. A partial shipment of 250 feet of 20 percent cold worked, Battelle-Northwest double vacuum melted, Type 316 stainless steel tubing was received and accepted for use in the Oxide Fuel Element Development Program (37-pin assembly). A shipment of 200 feet of 20 percent cold worked, double vacuum melted, Type 316 tubing, manufactured by planetary swaging was received for use in the characterization studies, and mechanical property testing was initiated.

3. CURRENT PROGRESS

TEST PROGRAM

The detailed test program, outlined in WARD-3791-26, and additional tasks defined in WARD-3791-29, WARD-3791-35, WARD-3791-41, WARD-4135-2, and WARD-4135-5 continued.

PROCUREMENT

Vacuum Melted Type 316 Stainless Steel Tubing for the Oxide Fuel Element Development Program (37-Pin Assembly)

A partial shipment of 250 feet of 20 percent cold worked, BNW VM(IVCEV) tubing has been received, bringing the total received to date to 500 feet.

Westinghouse Planetary Swaged, Vacuum Melted Tubing

A shipment of 103 feet of solution annealed, double vacuum melted, Type 316 stainless steel tubing, WARD VM(IVCEV), manufactured by planetary swaging from heat No. 91695, has been received for use in the characterization studies. The certified mechanical properties are listed in Table 1. This shipment completes the order.

STRUCTURAL CHARACTERIZATION OF PLANETARY SWAGED TUBING (Lots 49194 and 49193)

Hardness

Hardness results from two lots of planetary swaged tubing (one 20 percent cold worked and the other solution annealed) are given in Table 2, along

Table 1. Certified Mechanical Properties of Westinghouse Vacuum Melted, Planetary Swaged, Type 316 Stainless Steel Tubing (0.230-Inch OD x 0.015-Inch Wall)					
Heat Number	Fabrication Condition and Lot Number	Total Length (ft)	Superior Certified Uniaxial Room Temperature Mechanical Properties		
			Yield (ksi)	Ultimate (ksi)	Elongation (%)
91695	Planetary Swaged Solution Annealed Lot No. 49194	103	32.1	83.1	62.0
			33.6	84.1	64.0

Table 2. Diamond Pyramid Hardness of WARD Double Vacuum Melted, Type 316 SS Tubing, Fabricated by Plug Drawing or Planetary Swaging				
Lot Number	Fabrication	ASTM Grain Size	20% Cold Worked	Solution Annealed
42404	Drawing	5.5/6	$\bar{X}$ - 264 s - 10.9 V - 4.1% R - 245 - 274	
42405	Drawing	5/5.5		$\bar{X}$ - 138 s - 4.5% V - 3.3% R - 128 - 142
49193	Planetary Swaged	6	$\bar{X}$ - 325 s - 9.6 V - 3.0% R - 312 - 342	
49194	Planetary Swaged	6		$\bar{X}$ - 131 s - 4.0 V - 3.0% R - 125 - 136
$\bar{X}$ = Average hardness - DPH 7 indentations s = Standard deviation $V = \frac{s}{\bar{X}} \times 100$ = Coefficient of variation R = Range of measurements				

with results from comparable drawn tubing, fabricated to similar grain sizes from the same double vacuum melted heat. Included in the table are the average hardness from seven measurements for each lot and the standard deviation, coefficient of variation, and hardness range. The planetary swaged, annealed material has an average hardness of 131 DPH, which is not statistically different, at the 99 percent level of Student's "t" test, from the average hardness of the comparably drawn lot. However, there is a significant difference between the average hardnesses of the cold worked lots. The planetary swaged tubing has a hardness of 325 DPH compared to 264 DPH for the comparably drawn material. The standard deviations and the coefficients of variation indicate slightly more scatter in the data from the cold worked, drawn material, than from the other three lots.

All of these measurements were made at the approximate mid-wall position in transverse sections of the tubing. Hardness surveys across the wall of the tubing will be conducted during the next report period.

Grain Shape, Size, and Structure

The solution annealed, planetary swaged lot exhibits an equiaxed grain structure in both longitudinal and transverse sections. The cold worked lot consists of equiaxed grains in the transverse section, and slightly elongated grains in the longitudinal sections. Both planetary swaged lots have a grain size of ASTM 6.

The cold worked, planetary swaged lot appears to have a higher frequency of deformation bands than the corresponding drawn lot in spite of fabrication to the same degree of nominal cold work, based on percent cold reduction of cross-sectional area of the tubing.

These planetary swaged materials did not exhibit regions of finer grains near the inside and outside surfaces of the tubing as observed by Davies;^[2] however, they had only 20 percent reduction by planetary swaging. It appears that, to achieve the duplex grain structure reported by Davies,^[2] (to give enhanced mechanical properties), either greater reduction by planetary swaging or a different reduction schedule is required.

Investigation of this fabrication variable is included in the proposed work program for FY-1971.

Inside and Outside Surface Morphology

Examination of the inside and outside surfaces of the as-fabricated planetary swaged, tubing lots shows some differences from the corresponding drawn materials. The outside surfaces of both planetary swaged lots have a higher luster than the drawn materials. The existence of grain structure on the outside surface of the annealed lot indicates very little, if any, surface grinding. Both lots have shallow circumferential grooves, generally less than three microns deep, that are both narrower and fewer in number than in the drawn materials. Each lot also has a few shallow longitudinal scratches and some very shallow helical scratches.

Both lots contain angular equiaxed surface cavities up to 10 microns deep; this surface defect was not observed in the drawn materials. The tentative interpretation is that these cavities are the result of spalling which could probably be eliminated by optimizing the swaging procedure.

Examination of the inside surfaces showed readily observable grain structure in the annealed tubing, and indications of a distorted grain structure in the cold work tubing. The inside surfaces of both lots contained short, shallow longitudinal grooves. The groove frequency was higher in the annealed lot than in the cold worked lot.

Comprehensive Analysis of Planetary Swaged Tubing

Comprehensive structural characterization continued during the report period for the two planetary swaged lots. Pole figures ($\{111\}$ and $\{200\}$) have been obtained for both of the planetary swaged lots and for the corresponding plug drawn lots. Interpretation of the results is in progress. In addition, scanning electron microscopy of the inside and outside surfaces of the two planetary swaged lots is in progress. Extraction replicas and bulk extractions from both lots are also being analyzed.

Characterization of several heat treated specimens continued. A comparison, using scanning electron microscopy, of etched sections from plug drawn and planetary swaged 20 percent cold worked tubing, which had been given the "Garofalo" heat treatment ($900^{\circ}\text{F}/24\text{ Hr} + 1300^{\circ}\text{F}/216\text{ hr}$), showed pronounced differences in the distribution of the precipitates (see Figure 1). The planetary swaged material had a much higher concentration of intragranular precipitates and fewer grain boundary precipitates. Extraction replicas and bulk extractions from these specimens are being analyzed.

Classification of Characterization of Post Test Stress Rupture Specimens

Sixty-five post test stress rupture specimens from various lots of tubing have been classified according to rupture morphology. Examples of the rupture types, listed below, are shown in Figure 2.

Type 1 - Pin hole or fine cracks less than 3 mm long.

Type 2 - Splits greater than three mm long, sometimes opening with a flap.

Type 3 - Specimen ruptured into multiple pieces.

Table 3 lists the distribution of rupture types according to material and stress level. Several general observation can be made:

1. The cold worked planetary swaged material tends to rupture with a Type 1 fracture.

(a) DRAWN TUBING VM (IVCEV)

(b) PLANETARY SWAGED VM (IVCEV)

Figure 1. Scanning Electron Micrographs From Polished and Etched Sections of 20 Percent Cold Worked Tubing, Aged at 900°F for 24 Hours plus 1300°F for 216 Hours

3640-1

(a) TYPE 1 - ENLARGED VIEW OF RUPTURE SHOWING FINE CRACK

(b) TYPE 2 - RUPTURE SHOWING OPEN FLAP

(c) TYPE 3 - MULTIPLE PIECE RUPTURE, MANDREL
IN PLACE

Figure 2. Biaxial Stress-Rupture Types
3640-2

Table 3. Classification of 316 SS Biaxial Stress Rupture-Fracture

Melt	Condition	ASTM Grain Size	Stress x 1000 psi																		
			14	16	18	19	20	21	22	23	24	26	27	28	29	30	32	35	37	40	41
CEV	1. PD-CW	9/95					2		1		1	1		2		1					
	2. PD-ANN	8	1	1	2		2		1		2										
	3. PD-CW	5.5/6					1		1		1	1		1		2					
IV	5. PD-CW	9					1		2		2	2		2		1					
	7. PD-CW	5.5/6					1		1		1	2		1		1					
IVCEV	9. PD-CW	9			1		1,2		2		3,2	1	1	1		2		2	3	3	
	10. PD-ANN	8	3	1	2		3,2		2		2	2		2		3	3				
	11. PD-CW	5.5/6					1		2		2	1		2		3	1				
	15. PD-CW GHT	9					1		1		3	3		3		3					
	19. PS-CW	6					1		1		1	1		1		1	1				2
	20. PS-ANN	6		2	2	2		2		3		2			3						

1. Pinhole
2. Split
3. Pieces

PD - Plug Drawn

PS - Planetary Swaged

CW - 20% Cold Worked

ANN - Annealed

GHT - Garofalo Heat Treat

CEV - Consumable Elec.

IV - Induction Vac.

IVCEV - Consumable Elec.
Induction Vacuum

2. The annealed materials tend to fail with high fraction of Type 2 or Type 3 ruptures.
3. The cold worked, plug drawn, materials are intermediate between the annealed and the cold worked, planetary swaged materials.
4. In general, the tendency for Type 1 rupture is greater at lower stresses.

Microstructural Characterization of Post Test Stress Rupture Specimens

Table 4 summarizes the biaxial stress rupture test conditions and the identification of five of the post test specimens currently being evaluated microscopically. The preliminary observations are as follows:

1. The four specimens which contain Type 1 (fine crack) fractures showed maximum diametrical strain in the area of the cracks.
2. The maximum strains for the four specimens containing small cracks are listed in Table 4. The annealed drawn specimen has the highest strain, and the cold worked, planetary swaged specimen has the lowest strain. The cold worked, drawn specimens are intermediate.
3. Annealed specimens containing Type 1 fractures showed non-uniform wall strain. The wall thickness in the vicinity of the rupture is significantly smaller than the wall thickness diametrically opposite the rupture, when viewed in the transverse section. The relative reduction in wall thickness was as much as 20 percent. A similar effect was observed in cold worked specimens, but to a much lesser extent.
4. Preliminary metallographic results show that both the drawn and planetary swaged, cold worked specimens contain numerous creep voids near the fractures and fewer voids away from the fractures. Some of the creep voids are connected to the surfaces of the specimens.
5. Very preliminary results from the annealed specimen with Type 1 rupture indicate that this specimen has a low density of creep voids relative to the cold worked materials.
6. Only the planetary swaged specimen has been examined in detail. The creep voids in this specimen generally lie on grain boundaries, and at least some are "r" type voids. The larger voids show intergranular grain separation.
7. The outside surface of the specimens, which were tested in air, show two oxidation layers of slightly different color and reflectivity. The cracks and voids connected to the surface also show the double oxidation layer.

[illegible]

(a) DRAWN TUBING VM (IVCEV) 80x
20% COLD WORKED

(c) PLANETARY SWAGED TUBING VM (IVCEV) 80x
20% COLD WORKED

(b) DRAWN TUBING VM (IVCEV) 200x
20% COLD WORKED

(d) PLANETARY SWAGED TUBING VM (IVCEV) 400x
20% COLD WORKED

Figure 3. Taper Sections Post Test Type 1 Stress-Ruptures Showing Creep Voids

(a) DRAWN TUBING VM (IVCEV) 60x
20% COLD WORKED

(c) DRAWN TUBING VM (IVCEV) 60x
SOLUTION ANNEALED

(b) DRAWN TUBING VM (IVCEV) 200x
20% COLD WORKED

(d) DRAWN TUBING VM (IVCEV) 200x
SOLUTION ANNEALED

Figure 4. Transverse Sections Post Test Type 1 Stress-Ruptures. The Main Cracks Propagate From the Outside Surface to the Inside Surface of the Tube Wall in Both Materials

Table 5. Biaxial Stress-Rupture Data for Type 316 Stainless Steel Tubing

Lot	Material Condition	Tubing Dimension (in.)	Nom. Temp. (°F)	Test Temp. (°F)	Stress (ksi)	Rupture Time (hr)	Rupture Classification
42395	CEV-ANN-FG	0.015	1300	1295	14	696.1	1
42395	CEV-20% CW-CG	0.015	1300	1305	30	33.7	2
↓	↓	↓	1300	1293	28	89.7	1
↓	↓	↓	1300	1299	24	185.2	1
↓	↓	↓	1300	1303	22	392.2	1
↓	↓	↓	1300	1290	20	514.2	1
42395	CEV-20% CW-CG	0.015	1350	1346	26	27.7	1
42400	IV-20% CW-CG	0.015	1300	1285	30	42.3	1
↓	↓	↓	1300	1300	28	49.0	1
↓	↓	↓	1300	1295	26	80.5	2
↓	↓	↓	1350	1350	24	40.5	1
↓	↓	↓	1350	1350	22	76.3	1
42400	IV-20% CW-CG	0.015	1350	1346	20	122.8	1
42402	IVCEV-20% CW-FG	0.015	1200	1201	40	51.1	3
↓	↓	↓	1200	1207	37	68.9	3
↓	↓	↓	1250	1241	35	67.6	2
↓	↓	↓	1300	1313	30	26.6	2
↓	↓	↓	1300	1294	27	140.2	1
↓	↓	↓	1300	1312	20	341.8	2
↓	↓	↓	1300	1294	24	395.6	2
↓	↓	↓	1300	1295	22	365.0	2
42402	IVCEV-20% CW-FG	0.015	1300	1314	18	557.3	1
42403	IVCEV-ANN-FG	0.015	1200	1203	32	7.7	3
↓	↓	↓	1200	1203	30	20.0	3
↓	↓	↓	1200	1211	26	59.5	2
↓	↓	↓	1250	1243	28	11.6	2
↓	↓	↓	1250	1240	20	219.5	3
42403	IVCEV-ANN-FG	0.015	1300	1290	20	113.3	2
42404	IVCEV-20% CW-CG	0.015	1200	1215	32	354.5	1
			1200	1203	30	1081.3	3
49193	IVCEV-20% CW-Plan. Sw.	0.015	1200	1200	42.5	58.0	2
			1300	1284	32	124.6	1
49193	IVCEV-20% CW-Plan. Sw. + GHT	0.015	1300	1290	29	16.1	2
			1300	1294	26	42.8	1
49194	IVCEV-Plan.Sw.-Sol. Ann.	0.015	1300	1316	29	1.4	3
↓	↓	↓	1300	1316	26	4.4	2
↓	↓	↓	1300	1301	23	19.8	3
↓	↓	↓	1300	1297	21	45.8	2
↓	↓	↓	1300	1300	19	113.7	2
↓	↓	↓	1300	1297	18	234.6	2
↓	↓	↓	1300	1298	16.4	346.8	2

Figure 3 illustrates the creep voids observed in taper sections of the drawn and the planetary swaged cold worked specimens, and Figure 4 illustrates the transverse sections through Type 1 ruptures in the plug drawn cold worked and annealed specimens.

Mechanical Property Testing

Biaxial Stress Rupture Tests - Biaxial stress rupture tests were completed on 41 specimens during the report period. Table 5 summarizes the results and includes the material identification, stress, time to rupture, nominal and actual measured temperature, and classification of the ruptures. Long term tests are continuing.

The combined results for tests conducted at $1300(\pm 15^\circ\text{F})$ on various lots of 20 percent cold worked, WARD vacuum melted, Type 316 stainless steel tubing are shown in Figure 5, and in Figure 6 after normalization to 1300°F using a method described in a later section. Included in these figures is a plot of the United Kingdom (UK) data for 20 percent cold worked, vacuum melted,

Figure 5. Biaxial Stress-Rupture Results, 1300°F Nominal Temperature
3640-5

Figure 6. Biaxial Stress-Rupture Results, 1300 $^\circ\text{F}$, WARD Data Normalized 3640-6

Type 316 stainless steel tubing. Several observations can be made from the plots:

1. The WARD data follow a straight line when plotted log stress versus log time to rupture for the time range from less than 30 hours to greater than 700 hours.
2. The UK data also follow a straight line but with a steeper slope.
3. In the rupture time range, where data are available from both sources, the WARD data lie at higher stresses, have a shallower slope, and show no indication of a change of slope in this type plot.
4. Insufficient data are available to determine whether there is a break in the UK data line at some time less than 300 hours or whether the UK line crosses the WARD data line at shorter rupture times.

Figure 7. Biaxial Stress-Rupture Results, 1200°F Nominal Temperature
3640-7

Figure 7 is a similar plot for 1200°F data from WARD (not normalized), and UK for 20 percent cold worked tubing. The following observations can be made:

1. The WARD data generally follow the same straight line which lies at correspondingly higher stress levels than UK data.
2. The UK data show definite change in slope at about 600 hours, whereas WARD data show no change in slope in this type plot to at least 1000 hours.

WARD longer term tests are now in progress.

In both the current program and that planned for the future, biaxial stress rupture results are used to evaluate differences between melting practices, fabrication procedures, grain sizes, degree of cold work, defects, and other variables. Some of the differences in stress rupture results may be quite small and could be obscured by scatter in data. To help identify and evaluate the sources and data scatter in stress rupture results, the set of data listed in Table 6 was evaluated in detail.

The table includes thirteen stress rupture data points from WARD VM (IVCEV) 20 percent cold worked, fine grain size tubing having a nominal wall thickness of 0.015-inch (± 0.001). The total range of wall thickness variation reported by the supplier for this particular lot was 0.0009 inch. The data represent temperatures from 1241 to 1314°F, and stress levels from 18,000 to 35,000 psi. The data are grouped according to temperature range, nine points were obtained at 1300 ($\pm 15^\circ\text{F}$), three at 1268 to 1272°F and one at 1241°F. The data are plotted in Figure 8, using the same log

Table 6. Biaxial Stress - Rupture Data for WARD Double Vacuum Melted, Type 316 Stainless Steel Tubing (20 Percent Cold Worked, Grain Size 9)				
Nom Temp. (°F)	Test Temp. (°F)	Stress (ksi)	Rupture Time (hrs)	Chitty-Duval Parameter
1300 (±15)	1313	30	26.6	756.17
1300 (±15)	1294	27	140.2	770.84
1300 (±15)	1286	24	304.2	783.34
1300 (±15)	1294	24	295.6	789.60
1300 (±15)	1293	22	588.8	799.16
1300 (±15)	1295	22	365.0	792.73
1300 (±15)	1308	20	685.3	813.49
1300 (±15)	1312	20	341.8	804.26
1300 (±15)	1314	18	557.3	818.27
—	1268	32	67.8	742.77
—	1269	30	101.3	750.58
—	1272	28	173.9	760.81
—	1241	35	67.6	725.89

Figure 8. Biaxial Stress-Rupture Results, 1300°F, WARD Double Vacuum Melted Tubing, Grain Size 9, (Uncorrected Data)

3640-8

stress-log rupture time scales as for the previous plots. Two sets of limits are included. One set corresponds to stress variations due to ± 0.001 -inch in wall thickness; the other set of limits corresponds to the expected stress rupture variation due to $\pm 15^\circ\text{F}$. The estimation of the temperature limits is discussed below.

Various parameter plots were made of these data, including Larson-Miller, Manson-Haferd, Chitty-Duval, and Dorn. The Chitty-Duval plot was most useful for the present purpose.

Chitty Duval parameters were calculated for the thirteen data points according to the following relation.^[3]

$$d = T - m \log_{10} t_r$$

where

T = temperature, $^\circ\text{C}$

t_r = rupture time, hr

$m = \frac{dT}{d \log t}$ (There is a linear relationship between m and stress)

The "m" values used were taken from a standardized plot of stress versus m for Type 316 stainless steel.^[3]

The Chitty Duval plot of the thirteen points is shown in Figure 9. The points are fairly well grouped linearly when all points are considered, and very well grouped when only the 1300 ($\pm 15^\circ\text{F}$) points are considered, indicating at least reasonable applicability of the standardized m versus stress plot to these data.

The Chitty Duval results were applied to log stress, log rupture time plots as follows. The Chitty Duval m factor ($dT/d \log t$), which relates rupture time and temperature for a given stress, was used to estimate the $\pm^\circ\text{F}$ temperature limits on the log stress, log rupture time plot of Figure 8, and to normalize the thirteen data points to 1300°F . Figure 10 is a plot of the normalized data.

It is apparent that the scatter due to temperature is significantly reduced, and, in principle at least, this procedure could be used to eliminate the scatter in the data due to temperature variations, provided individual specimens, and test temperatures are measured, and the correct m values are used.

After correction for temperature, the residual scatter includes the effects of wall thickness variations. This source of scatter could also be significantly reduced by individual specimen measurements. It is possible to measure wall thickness by ultrasonics to ± 0.0001 -inch, which is one-tenth of the nominal

Figure 9. Chitty - Duval Plot WARD Double Vacuum Melted, 20 Percent Cold Worked Tubing, Fine Grain Size

3640-9

variation (± 0.001 -inch), and thus effect a reduction in scatter from this source by a corresponding factor of as much as ten. Installation of equipment suitable for this purpose is in progress.

This evaluation indicates that the scatter in stress rupture data can be greatly reduced in the log rupture time plots by combining the temperature correction (described previously) with accurate measurement of wall thickness, and continued measurement of test temperature of individual specimens. This evaluation also indicates that the large furnaces currently in use, which handle nine specimens simultaneously, can be used to generate a high level of data output of acceptable accuracy.

In addition to the application to temperature correction, the Chitty-Duval m factor has also been found useful in estimating expected rupture times, and selecting stresses for tests to be conducted at various temperatures.

Figure 10. Biaxial Stress-Rupture Results, 1300°F, WARD Double Vacuum Melted Tubing, Grain Size 9, (Corrected Data)

3640-10

Low Cycle High Strain Fatigue Tests - The objective of these tests is to develop a reliable technique for measuring the fatigue performance of Type 316 stainless steel cladding-type tubing under conditions of high strain and temperature. Although high temperature, high strain data are already available for Type 316 stainless steel, [4,5] these data were obtained on bar specimens, and it is not known if these results can be directly applied to thin wall tubing. In the current test program, the initial results [6] indicated areas in which the test specimen design was deficient. Modifications were subsequently incorporated in a revised specimen design. [7] The new specimen design, the testing procedure, and the results from the current tests are reviewed in the following paragraphs.

Strain cycle fatigue testing of the revised specimen design was completed. A total of four test runs were conducted at 1200°F, and consisted of two runs at an approximate axial strain range of ± 0.35 percent and two runs at an approximate strain range of ± 0.7 percent. Cycling was about a mean strain of zero. Table 7 summarizes the results of these tests, and a comparison is made in Figure 11 between these results, bar specimen data, [4] and data from the initial specimen design [6] at 1200°F. Figure 12 shows photographs of the failed samples, and micrographs of longitudinal sections of selected weld and fracture areas are shown in Figures 13 and 14.

In all cases, calculation of the axial strain at fracture required consideration of several correction factors to the nominal test dimensions. The first correction that had to be considered was the correction applied to the specimen test length. Although the nominal length of the specimen is 0.600-inch, this dimension has to be corrected following the welding of the specimen to the specimen grips. There are two possible correction factors which can be applied:

Table 7. Low Cycle Strain Fatigue Tests on Type 316 Stainless Steel Tubing at 1200°F					
Nominal Strain Range (in.)	Estimated Strain Range at Fracture (in.)	Actual Specimen Test Length (in.)	Strain at Fracture (%)	Cycles to Failure	Comments
0.0088	0.0082	0.596	1.38	85	Failure opposite mandrel end.
0.0087	0.0081	0.576	1.41	81	Failure opposite mandrel end. One weld cracked.
0.0043	0.0040	0.576	0.69	556	Failure opposite mandrel end.
0.0046	0.0043	0.588	0.73	690	Test stopped before com- plete failure. Cracks at one weld and opposite mandrel end.

Figure 11. Total Axial Strain Range Versus Cycles to Failure for Type 316 Stainless Steel at 1200°F

3640-11

(a) TOTAL STRAIN 1.41%;
FAILED AFTER 81 CYCLES

(b) TOTAL STRAIN 1.38%;
FAILED AFTER 85 CYCLES

(c) TOTAL STRAIN 0.69%;
FAILED AFTER 556 CYCLES

(d) TOTAL STRAIN 0.73%;
TEST STOPPED AFTER
690 CYCLES

Figure 12. Failed Samples From Low Cycle Strain Fatigue Tests
3640-12

(a) WELD INTACT

50x

(b) WELD FAILURE DUE TO BLOW-HOLE TYPE DEFECT

50x

Figure 13. Cross-Section of Welds Between Type 316SS Tubing and Test Fixture, After 690 Cycles at 1200°F Over a Strain Range of 0.73 Percent

3640-13

Figure 14. Location of Strain Cycle Fatigue Crack in Type 316SS Tubing
After 690 Cycles Over a Strain Range of 0.73 Percent at 1200°F

3640-14

1. The whole width of the weld, defined as that area showing weld microstructure, is excluded from the test length.
2. The parts of the weld which do not penetrate the tube through to the specimen grip are included in the test length.

In the current series, it was decided to adopt the second method as the one which more accurately represents the test length, although it is recognized that the fatigue properties of the weld areas are different from those of the annealed tubing. The determination of this correction was carried out on sectioned samples after testing.

The second correction factor concerns the strain range. During testing, axial strain was controlled by a linear variable differential transducer (LVDT), mounted on the bottom of the piston in the hydraulic testing machine.^[6] Strain was also measured at various times by a pair of clip gages attached to the specimen grips. The readings from the clip gages were at all times lower than those from the LVDT, sometimes by nearly 20 percent. However, the differential was not consistent and, as failure was approached, the differential was lowered (see Figure 15). It was concluded from extrapolation of plots such as Figure 15 that, at complete failure, the ratio of the LVDT reading to the clip gage reading was about 1.07. Subsequently, the LVDT readings at fracture were adjusted, using

Figure 15. Variation of (LVDT output/clip gauge reading) During Strain Cycle Fatigue Test at 1200°F.

3640-15

this factor, and the resultant strain value defined as the strain at fracture.

In the initial series of strain cycle fatigue tests with tubing specimens, [6] it was found necessary to apply corrections to the measured strain to allow for specimen buckling. The current series of tests were designed to reduce the possibility of the occurrence of buckling, and, in practice, no detectable buckling was noted under optical examination (Figure 12). (NOTE: although it would appear that the specimen which failed after 85 cycles suffered considerable buckling, in fact a surge in the electrical system of the testing equipment occurred after fracture and caused impact between the two halves. The gross buckling of this specimen is therefore illusory.) In the absence of buckling, it was not necessary to correct the strains on this account.

Another factor which can affect interpretation of the observations is the temperature profile along the specimen. As this is not accurately known, no allowances have been made for this factor. However, it is likely that

not all of the test length of the specimen is at 1200°F, the extremities being at lower temperatures. Thus the actual test lengths at 1200°F are almost certainly less than those given in Table 7. This, in turn, means the true percent strain ranges are probably greater than those given in Table 7.

Reviewing the results of the tests, the following observations are possible. The primary intention of the revised specimen design was to minimize buckling by providing internal support for the tubing over as much of the specimen length as possible. This was generally successful, with no detectable buckling being observed under optical examination. This is confirmed by the fact that these specimens have apparently longer fatigue lives than the earlier specimens, if the latter are not corrected for buckling (Figure 11). However, the tube samples still appear to have a shorter life than bar samples at the same strain range. This differential might be explained by consideration of the temperature profile of the specimen. As described earlier, it is conceivable that the actual lengths of the specimens which are at 1200°F are less than those given in Table 7; if this is so, the true percent strain ranges will be greater than those in Table 7. This will tend to bring the observations in closer correspondence with those from bar material.

On the subject of crack initiation and subsequent tube failure, it is apparent that, with the present design, tube cracks are primarily located opposite, or near to, the end of the support mandrel of the lower (mobile) specimen grip. No cracks were observed opposite the end of the support mandrel of the upper (static) test grip. This suggests that at least two factors are concerned in the crack initiation. The first of these would be the stress-raising effect associated with the loss of internal support at the mandrel end. However, if this was the only factor, it would be reasonable to expect cracks to appear opposite the mandrel ends of both the upper and the lower specimen grips. This is not observed in practice, which indicates that additional stress factors are associated with the lower specimen grips. At this time, the most likely second factor would appear to be temperature. The temperature profile of the specimen is not known exactly and it is conceivable that temperature high-spots could be located nearer the lower specimen grip than the upper grip. Also, the lower grip is mobile, thereby accentuating the possibility of encountering temperature variations. Whichever set of circumstances prevails, however, the resultant combination of higher local temperature and the stress-raising effect of the mandrel end would combine to produce the most favorable condition for crack initiation and growth.

One of the deficiencies noted in the initial tube tests was the lack of weld penetration and consequent crack initiation at welds. Although none of the current series of tests failed completely at a weld, two out of the eight welds cracked during testing. Microscopic examination of sectioned weld areas indicated that the cause of failure was not insufficient weld penetration, although more penetration is desirable. Instead, failure in the current tests is attributable to blow-hole type defects (Figures 12 and 13). This is not an insurmountable problem and can be rectified by increasing the weld current and introducing a negative pressure inside the tube.

A further refinement to be applied to future tests concerns strain measurement and control. In the current series, considerable discrepancy was noted between the strains recorded on the LVDT (which was used to control the tests), and those recorded by a clip-gage attached directly to the specimen grips. Further, this discrepancy was not consistent. It is proposed that in future tests, strain measurement and control will originate solely from clip-gages located on the specimen grips.

In conclusion, it is apparent that, following further refinement of experimental technique, it will be possible to obtain meaningful low cycle, high strain fatigue data on thin-wall tubing. These refinements include:

1. Accurate measurement and, if necessary, adjustment of the temperature profile along the test specimen.
2. Improved welding, aimed at increased weld penetration and reduced possibility of blow-hole type defects.
3. Measurement and control of strain, using clip-gages located on the specimen grips.
4. Reduction of the stress-raising effect opposite the mandrel ends by rounding off those ends.

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