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STAINLESS STEEL CLADDING DEVELOPMENT

QUARTERLY PROGRESS REPORT

FOR THE PERIOD ENDING MARCH 31, 1971

Approved by:

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Division of Reactor Development and Technology
Under Contract No. AT(30-1)-4210, Task 3

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SECTION 1 INTRODUCTION

1.0 GENERAL

This is the eleventh quarterly progress report and covers the work performed during the third quarter of FY-1971.

2.0 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 rods. 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.

3.0 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."
- WARD-4135-9 "Stainless Steel Cladding Development Quarterly Progress Report for the Period Ending March 31, 1970."
- WARD-4135-12 "Stainless Steel Cladding Development Quarterly Progress Report for the Period Ending June 30, 1970."
- WARD-4135-14 "Stainless Steel Cladding Development Quarterly Progress Report for the Period Ending September 30, 1970."
- WARD-4210T3-2 "Stainless Steel Cladding Development Quarterly Progress Report for the Period Ending December 31, 1970."

4.0 SUMMARY OF CURRENT PROGRESS

Under Task SSDA-210, the major activities during the report period were directed to the completion of the Vacuum Melted Steels Task, preparation of a topical report, and continuation of the Defects Evaluation Task.

The following tests, measurements, and observations were made during the report period completing the planned test program for the Vacuum Melted Steels Task, except for identification of precipitates in post-stress rupture specimens:

Seven long-term stress rupture tests were completed. Seven tested specimens and two control specimens were prepared in special mounts, and cathodic vacuum etched. The microstructures were evaluated for grain size and shape, and cavity distribution.

Strain profile measurements were made for 17 additional post-stress rupture test specimens bringing the total number of specimens evaluated by this approach to 53.

Rupture ductilities and shoulder ductilities were measured for each of these specimen and evaluated with respect to test stress and material properties.

A draft of a topical report covering the Vacuum Melted Steels Task and a previously completed subtask on Weldability was submitted for publication as a formal report.

As part of the Defects Evaluation Task, seven biaxial stress rupture tests in an argon atmosphere were completed for 20 percent cold worked tubing, containing intentional defects of various sizes and orientations. An indication of a defect length effect was observed.

The tubes containing numerous OD surface defects, resulting from previous repeated handling were: 1) used to test the eddy current and ultrasonic equipment and procedures; 2) to set confidence limits on the observed responses; 3) to compare responses by the two methods with EDM notch standards of various sizes, orientations, and locations.

Twelve items from a total of 23 tubing lots and sublots, ordered for the Stainless Steel Cladding Development Program, have been received. Although this order is not complete, these items are sufficient to meet the needs of the Defects Evaluation Task.

The replica procedure for internal tube surfaces has been up-graded during the report period but thus far has been applied to only a limited number of specimens.

SSDA-110 PROJECT ADMINISTRATION

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

1.0 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.

2.0 PRIOR WORK

Schedule 189a/Work Plan for FY-1971 was prepared and submitted to the New York Operations Office. Technical work has continued on the basis of the work plan. The project is divided into the following tasks for FY-1971 administrative control.

SSDA-110 Project Administration

SSDA-210 Evaluation of Austenitic Stainless Steel Cladding

3.0 CURRENT PROGRESS

The quarterly progress report, WARD-4210T3-2, for the period ending December 31, 1970 was prepared and distributed.

A topical report, covering the Vacuum Melted Steels Task, is being prepared for submittal in May 1971.

SSDA-210 EVALUATION OF AUSTENITIC STAINLESS STEEL CLADDING

T. R. Padden, W. E. Ray, E. J. Tarby, and K. C. Thomas

1.0 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.

2.0 PRIOR WORK

During the first year (FY-1969), a test program was prepared and initiated with 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 by 0.016-inch wall. Extensive biaxial burst testing at 850, 1000, 1200, and 1300°F and chemical and microstructural evaluation of the tubing were performed, and biaxial stress rupture testing was initiated. This part of the program was completed during the second year and included a thermal aging study of several lots of the air melted materials aged for times up to 5000 hours.

A weldability subtask, to determine the effect of degree of cold work on weldability of Type 316 stainless steel tubing, was also completed.

The characterization and testing program was extended to a systematic investigation of vacuum melted, Type 316 stainless steel, plug drawn tubing. Twelve lots of tubing ordered during FY-1969 and received at the beginning of FY-1970 were extensively tested and characterized during FY-1970 and the beginning of FY-1971. This tubing included the twelve combinations of three vacuum melting practices, two grain sizes, and the two finished conditions (20 percent cold worked and solution annealed). In addition, two lots of planetary swaged tubing were procured and included in the test program.

General characterization of the vacuum melted tubing has been completed, including chemical analysis, light microscopy, and hardness measurements.

Comprehensive structural characterization was completed for two of the plug drawn lots and the two planetary swaged lots, all fabricated from double-vacuum-melted steel. These characterizations included transmission and scanning electron microscopy, electron and x-ray diffraction, and texture analysis by pole figures. The as-received cold worked, plug drawn lot was also characterized by electron probe analysis.

Biaxial tensile testing at room temperature and five elevated temperatures was completed for the 14 lots of vacuum melted steel tubing. Results were compared and evaluated for the effects of the independent variables on the properties of tubing.

Extensive biaxial stress rupture testing was performed at 1300°F in air, and selected tests were conducted at 1200°F. Preliminary evaluations were made at various stages of the test program. Long-term tests are still in progress.

Post-test classification of stress ruptured specimens according to rupture morphology, material variables, and test conditions continued throughout the test program.

Strain profile and wall thickness measurements were made of selected post-test specimens along with metallographic evaluations.

A paper entitled "Development of Type 316 Stainless Steel Tubing for LMFBR Fuel Element Cladding," by T. R. Padden, W. E. Ray, H. J. Snyder, and K. C. Thomas, was presented at the Winter Meeting of the ANS in Washington, D. C.

A summary of the Vacuum Melted Steels Task was initiated in preparation for issuance of a topical report.

In preparation for the "Defects Evaluation Task," included in the work program for the current fiscal year, nondestructive test equipment was procured and installed, and preliminary testing was initiated.

Tubing required for this defects evaluation test program was order from Superior Tube Company. This order consists of 23 lots and sublots, representing various combinations of fabrication procedures, finishing steps, and acceptance tests. The order was specified such that three severity levels of naturally occurring defects should be obtained.

3.0 CURRENT PROGRESS

3.1 Procurement and Handling

Twelve items from a total of 23 tubing lots and sublots that were ordered for the Stainless Steel Cladding Development Program have been received. The items received are sufficient to meet the requirements of the Defects Evaluation Task described in the work program. Superior Tube Co. had difficulty meeting the specifications for some of the developmental tubing lots which were to be fabricated by planetary swaging. The current program is not limited by these difficulties, however, since the task for investiga-

tion of planetary swaging had been de-emphasised. Negotiations to close the order are now underway.

A 48-inch notch standard has been received from Kenmar Engineering. This standard was fabricated from Superior lot 42402 tubing as per WADCO drawing H 3 32446, and contains artificial defects 0.7, 1.0, and 1.3 mils deep.

Wall thickness and eccentricity standards have been received from U. S. Tool & Die, Inc. The standards were fabricated from Cartech heat No. 91695 and will be used with air gage and ultrasonic equipment.

A velocity calibration plug has been fabricated from Cartech heat No. 91695 for use with the ultrasonic equipment.

3.2 Tubing Characterization

Characterization of Cartech tubing has been initiated according to the procedures used previously[2-11] for Superior Tube Co. material. This Cartech cladding was purchased as part of the order for the 37-pin assembly (WSA-3). In addition to these characterizations, the tubing will be nondestructively tested at ARD and the results compared with those supplied by WADCO, and then stress rupture tested for comparison with the Superior Tube Co. tubing recently purchased for the defects evaluation task.

3.3 Mechanical Property Tests

3.3.1 Biaxial Stress Rupture in Air - Vacuum Melted Steels Task

The results of seven biaxial stress rupture tests performed in air are presented in Table 1.

Table 1. Biaxial Stress Rupture Data for Type 316 Stainless Steel Tubing in Air							
Lot	Material Condition	Wall Dimension (in.)	Nom. Temp. (°F)	Test Temp. (°F)	Stress (ksi)	Rupture Time (hr)	Rupture Type
42394	CEV-20% CW-FG	0.015	1300	1291	12	2312.2	pinhole
42394	CEV-20% CW-FG	0.015	1300	1303	10	2734.4	pinhole
42398	IV-20% CW-FG	0.015	1300	1315	12	1109.4	pinhole
42398	IV-20% CW-FG	0.015	1300	1301	10	2445.9	pinhole
42402	IVCEV-20% CW-FG	0.015	1300	1301	10	3446.5	pinhole
42403	IVCEV-ANN-FG	0.015	1300	1316	10	3533.0	pinhole
49193	IVCEV-20% CW-PS-CG	0.015	1300	1305	7.6	2256.5	pinhole
CW - Cold Worked		IV - Induction Vacuum					
ANN - Annealed		IVCEV - Consumable Elec. Plus Induction Vac.					
FG - Fine Grain		CEV - Consumable Elec.					
CG - Coarse Grain		PS - Planetary Swaged					

These were all long-term tests, and they complete the Vacuum Melted Steels Task. Remaining in test are several very long-term samples and one artificially defected sample to serve as a spot check on air-tested defected specimens.

These new data points generally confirm the observations and interpretations previously described^[10,11] for the various tubing lots investigated as part of this Vacuum Melted Steels Task.

3.3.2 Biaxial Stress Rupture in Argon - Defects Evaluation Task

The results of six biaxial stress rupture results in argon are presented in Table 2.

Table 2. Biaxial Stress Rupture Data for Type 316 Stainless Steel Tubing in Argon								
Sample No.	Lot	Material Condition	Wall Dimension (in.)	Nom. Temp. (°F)	Test Temp. (°F)	Stress (ksi)	Rupture Time (hr)	Rupture Type
4	42402	IVCEV-20% CW-FG	0.015	1300	1298	23	328.1	split
5	42402	IVCEV-20% CW-FG	0.015	1300	1302	23	319	pinhole
9	42402	IVCEV-20% CW-FG	0.015	1300	1305	23	140.3	pinhole
2	42402	IVCEV-20% CW-FG	0.015	1300	1303	23	305.5	pinhole
6	42402	IVCEV-20% CW-FG	0.015	1300	1305	23	159	split
7	42402	IVCEV-20% CW-FG	0.015	1300	1302	23	148.7	split
Specimen Description(a)								
Sample No.	Defect Location And Type		Length (in.)	Width (in.)	Depth (in.)	Failure Location		
4	L - ID		0.030	0.0022	0.001	not at defect		
5	L - ID		0.030	0.0022	0.0015	not at defect		
9	L - ID		0.240	0.0022	0.0016	at defect		
2	L - OD		0.030	0.0022	0.00105	not at defect		
6	L - OD		0.240	0.0022	0.00054	not at defect		
7	L - OD		0.240	0.0022	0.00108	at defect		
CW - Cold Worked					L - Longitudinal			
FG - Fine Grain					ID - Inside Diameter			
IVCEV - Consumable Elec. Plus Induction Vac.					OD - Outside Diameter			
(a)Intentional defects were produced by electro discharge machining (EDM)								

Three specimens contained intentional ID defects and three intentional OD defects. Only two specimens failed in the general vicinity of a defect; the others failed at significant distances away from defect locations. However, the two specimens which failed at the defect contained much longer defects than the other four (0.240-inch long compared to 0.030-inch long). This indication of a length effect will be studied in greater detail.

Post-test characterization and metallographic examination of these specimens are planned for the next period.

3.3.3 Uniaxial Creep

The second uniaxial creep unit utilizing a platinum strain gage measuring technique is now in operation. Creep testing is progressing satisfactorily at 1200°F on two samples of Type 316 stainless steel (20 percent cold worked) from Superior lot 42402. One unit at 12,000 psi has accumulated 2000 hours, and has shown no measurable creep. A second unit has accumulated 1000 hours at 15,000 psi. Preliminary results up to 0.11 percent strain at 925 hours show an average creep rate of 1.175×10^{-4} percent per hour at 15,000 psi.

3.4 POST-TEST STRESS RUPTURE SPECIMEN CHARACTERIZATION

3.4.1 Vacuum Melted Steel Task - Metallography

Transverse sections from seven tested specimens and two as-received specimens selected from the stress rupture test program were prepared for metallographic examination by cathodic vacuum etching. The location of the sections was about one-half to one inch away from the rupture in the specimens. The cathodic vacuum etching procedure is especially useful for evaluating grain size in the presence of extensive precipitation and for evaluating cavities in the microstructure. These examinations complete the metallographic studies planned for the Vacuum Melted Steels Task.

The microstructure after long-term stress rupture test at 1300°F compared to that of the as-received material is shown in Figure 1 for the cold worked, planetary swaged tubing (lot 49193). It is apparent that the structure near the OD of the tube has recrystallized to smaller grain size during the long-term test. The post-test microstructures for short and long-term tests, shown in Figures 2a and b, illustrate several other observations made for this tubing lot. Grain boundary cavities were present in specimens before and after the break in the stress rupture time curve; the concentration of the cavities increased with rupture time at 1300°F, but before the break in the curve, the highest concentration of cavities was near the OD, and that after the break near the ID. This shift in the location of the cavity concentration is correlated with a shift in the rupture initiation site from the OD in the short-term tests to the ID in the long-term tests for this lot (49193).

For the plug drawn, cold worked specimens (lot 42402) there was no indication of recrystallization based on grain size in the sections examined (Figure 3). Although the grain boundary cavity concentration increased with

OD

ID 500X

(a) AS-RECEIVED SPECIMEN, 20% COLD WORKED, ASTM GRAIN SIZE 6

OD

ID 500X

(b) POST-TEST STRESS RUPTURE SPECIMEN ONE INCH FROM RUPTURE PLANE, T_r 1493 hr, 10,500 psi, 1300°F

Figure 1. Composite Micrographs Across the Tube Wall - Planetary Swaged Tubing, Lot 49193, Cathodic Vacuum Etch 4199-

Figure 2. Comparison of Post-Test Microstructures from Short and Long-Term Stress Rupture Tests for Two Lots of Cold Worked, Type 316 Stainless Steel Tubing - Cathodic Vacuum Etched

4199-

rupture time and reduced test stress (Figure 2c and d), the highest concentration remained near the OD, and there was no shift in rupture initiation site from OD to ID in this lot (42402). Rupture initiated at the OD over the whole range of test conditions.

It was shown previously[10, 11] for the planetary swaged and the plug drawn, cold worked lots, that the quantity of large intermetallic-type precipitates increased with increased rupture time and the concentration was higher in the OD half of the tube wall than in the ID half in both tubing lots.

Very long term-tests from both the annealed, planetary swaged and the annealed, plug drawn lots showed pronounced elongation of the grains in the hoop direction and only a very few grain boundary cavities (Figure 4). Careful examination of the section from the plug drawn, annealed specimen with a rupture time of 2424 hours (illustrated by Figure 4b) showed that it had about the same frequency of cavities as the 26.6 hour specimen from the cold worked lot tested at the same nominal temperature (1300°F) illustrated by Figure 2c.

For the two annealed lots it was observed that rupture initiated at the OD over the whole range of test conditions. It was shown previously[10, 11] that both annealed lots showed the presence of some of the large intermetallic-type precipitates throughout the wall after long-term test and that the plug drawn lot had a significantly higher concentration than the planetary swaged specimen.

More detailed consideration of these and the previous observations is given in the topical report covering the Vacuum Melted Steel Task.[12]

3.4.2 Strain Profile Measurements

The $\Delta D/D$ measurements planned for the Vacuum Melted Steels Task have also been completed. Strain profile measurements were made for an additional 17 specimens selected from the stress rupture test program bringing the total to 53 specimens evaluated by this approach. Rupture ductilities, measured as $\Delta D/D$ corrected for the width of rupture, were plotted as a function of stress for each lot of material. Shoulder ductilities, also measured as $\Delta D/D$ and defined here as the average of the measurements ± 1 inch from the rupture, were similarly plotted.

In general it was found that there was non-uniform average strain ($\Delta D/D$) along the length of the specimens, the rupture location had the greatest strain in almost every specimen, the annealed materials had much greater $\Delta D/D$'s than the cold worked materials, and the specimens that had the highest average $\Delta D/D$'s usually had the highest diameter non-uniformity along the length (i.e., localized bulging). For cold worked, plug drawn material, both increased grain size and lower test temperature (1200°F nominal) resulted in lower ductilities. In some specimens there were two or more local bulges along the length; this observation was more frequent in the low stress, long-term tests.

- (a) CATHODIC VACUUM ETCHED, AS-RECEIVED, 20% COLD WORKED, ASTM GRAIN SIZE 9
- (b) CATHODIC VACUUM ETCHED POST-TEST RUPTURE SPECIMEN, $T_r = 2368$ hr, HOOP STRESS = 12,000 psi, 1303°F AIR ATMOSPHERE
SECTION: 1 in. FROM RUPTURE PLANE
- (c) CHEMICAL ETCH POST-TEST RUPTURE SPECIMEN, $T_r = 2368$ hr, HOOP STRESS = 1303°F AIR ATMOSPHERE
SECTION: IN RUPTURE PLANE, 20 DEGREES FROM RUPTURE

Figure 3. Composite Micrographs Across the Tube Wall - Plug Drawn Tubing, Lot 42402

OD

ID

225X

(a) PLANETARY SWAGED LOT 49194 ANNEALED CONDITION, ASTM GRAIN SIZE 6, T_r 2494 hr, 11,800 psi, 1300°F

OD

ID

225X

(b) PLUG DRAWN LOT 42403 ANNEALED CONDITION, ASTM GRAIN SIZE 8, T_r 2424 hr. 11,500 psi, 1301°F

Figure 4. Long-Term, Post-Test Stress Rupture Specimens - Transverse Microstructures Across Wall in Sections One Inch From Rupture Plane - Cathodic Vacuum Etch

4199-

Figures 5, 6, and 7 illustrate the rupture and shoulder $\Delta D/D$ results. In general, there is reduction in ductility with reduced hoop stress. Shoulder ductility, defined as the average of the $\Delta D/D$ measurements one inch on each side of the rupture, follows the same general curve shape as the rupture ductility but at a lower level. The ratio of rupture to shoulder ductility is treated in later paragraphs.

Comparison of ductility by melting practice is shown in Figure 5 for the plug drawn, cold worked, fine-grained condition. There is slightly greater ductility associated with double vacuum-melting practice (lot 42402 - IVCEV), and little, if any, difference between the two single vacuum-melting practices (lots 43494 - CEV and 42398 - IV).

Figure 6 illustrates comparisons of ductilities associated with grain size variations, test temperature, and fabrication procedure for the cold worked, double vacuum-melted material lots. For conditions where there is a mixed-type rupture (pinholes and splits) there does not appear to be a discontinuous change in ductility associated with change in rupture morphology. Comparison of fine-grained Lot 42402, ASTM 9 with coarse-grained Lot 42404, ASTM 6 shows that at a 1300°F test temperature, the coarse-grained lot has lower ductility over the stress range investigated (29,000 psi to 15,000 psi). Comparison of these results at 1300°F (nominal) with 1200°F data from the same lots showed a significant drop in ductility associated with lower test temperature.

The coarse-grained, planetary swaged lot (49193) had generally higher ductility than the coarse-grained, plug drawn lot (42402), but lower ductility than the fine-grained, plug drawn lot (42402).

The one point for the micropeened lot (42402) fell on the line for untreated lot 42402 data, indicating little or no effect of micropeening on the ductility of cold worked tubing.

Heat treatment of the planetary swaged material (lot 49193) at 900°F for 24 hours, plus 1300°F for 216 hours increased ductility over the measured stress range (26,000 to 18,000 psi).

There were too few data points for the amount of scatter in the rupture ductility data for the two annealed lots measured to show an effect of stress on rupture ductility (Figure 7). However, the scatter in the shoulder ductility data was less and these data indicate a downward trend in ductility with reduced stress for both the annealed, plug drawn lot (42403) and the annealed, planetary swaged lot (49193). With the scatter of the data obtained, there appears to be little difference between these two annealed lots in spite of the difference in grain size. The one point measured for a 1200°F plug drawn specimen indicates a drop in ductility associated with the lower test temperature.

An important observation made in the stress rupture testing program was that for the low stresses these two annealed lots have greater stress rupture life than the comparable cold worked lots. These $\Delta D/D$ data show that the annealed lots also have much greater ductility.

Figure 5. Single and Double Vacuum-Melted, Type 316 Stainless Steel Tubing Post-Test Air Atmosphere Stress Rupture - Fine Grain Size, 20 Percent Cold Worked Condition

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Figure 6. Double Vacuum-Melted, Type 316 Stainless Steel Post-Test Air Atmosphere Stress Ruptures - 20 Percent Cold Worked Condition

Figure 7. Double Vacuum-Melted, Type 316 Stainless Steel Tubing, Post-Test Air Atmosphere Stress Rupture - Annealed Condition

The ratio of rupture to shoulder ductility was calculated for each of the 53 specimens measured. Considering all lots together there was no definite change in this ratio with change in stress. However, there was indication in some of the lots that there may be a decrease in the ratio with increasing stress. A program with more data points per lot would be required to determine if such a relation exists.

A distinction could be made, however, between the cold worked tubing and the annealed tubing. Average ratios were calculated for the 1300°F data for each lot; the results are as follows:

Cold Worked		Annealed	
Lot	Ratio = $\frac{\text{Rupture } \Delta D/D}{\text{Shoulder } \Delta D/D}$	Lot	Ratio = $\frac{\text{Rupture } \Delta D/D}{\text{Shoulder } \Delta D/D}$
42402	1.37	42403	2.31
42404	1.38	49194	2.16
42394	1.21		
42398	1.26		
49193	1.29		
49103 plus Heat. Treat.	1.09		

The factors contributing to the observed differences in the ratios probably include the total ductility at rupture and perhaps mechanical differences in the tubing (such as wall thickness variation in the pre-test tubing).

3.5 NON-DESTRUCTIVE TESTING

The non-destructive test facilities at ARD were procured and put into operation with Westinghouse funds. The equipment consists of the following:

EDDY CURRENT UNIT

One Nortec NDT-1 Eddy Current Tester
 One Tektronix 564-B Storage Oscilloscope
 One Nortec Drive Mechanism
 One Superior 16-B Powerstat Speed Control
 One Brush (6 channel) 260 Strip Chart Recorder

AIR GAGE UNIT

Two Federal 232 Amplifiers
 Two Federal Air Electronic Transducers

One Federal 0.200 inch ID Probe
One Federal 0.230 inch OD Ring
One Westinghouse Tube Transport
One Federal MDR4 Regulator
One Federal AFL-9 Filter
One Hankinson Refrigeration Type Drier

ULTRASONIC UNIT

1. Flaw Detection:

Four Nortec 102 Plug-in Modules
Two Tektronix 127 Preamplifiers
One Tektronix RM15 Oscilloscope
Four Nortec 10 MHz Transducers
One Brush (6 channel) 260 Strip Chart Recorder
One Tac-Tic Transport System

2. Wall Thickness and Eccentricity Unit:

One Sonics VTR 12 Visual Trace Readout
One Sonics DTG2R Digital Thickness Gage
One Sonics TAM-3 Thickness Alarm Module
One Tektronix R561B Dual Trace Oscilloscope
One Honeywell 117-06 Preamplifier
One Honeywell 1508 Visicorder
One Aerotech 10 MHz Transducer
One Tac-Tic Transport System

The eddy current unit is shown in Figure 8 and the ultrasonic unit is shown in Figure 9.

3.5.1 Eddy Current Testing

This unit has operated successfully over a period of several months. Calibration curves were constructed from 100 test runs on the standard manufactured by Kenmar Engineering, Beaver Falls, Pa. shown in Figure 10 (Superior Lot No. 42402 - Figure 5 of RDT-E-13-8). The certified notch depths and ARD measurements are shown in Table 3. The test runs were made at a rate of ten per day over a ten day period. The data were analyzed and curves of pulse height versus notch depth were constructed for a confidence level of 95 percent. These curves are shown in Figure 11.

The procedure adopted in eddy current testing for thin wall tubing is to set the unit to obtain a maximum pulse height on the standard 1-1/2 mil axial OD notch, keeping it within the control band. The pulse heights of the other notches are then checked to determine whether they are within their control bands. All adjustments to the unit are made with reference to the 1-1/2 mil axial OD notch.

Figure 9. Ultrasonic Unit for Determining Defects, Wall Thickness, and Eccentricity

Figure 8. Eddy Current Unit for Determining Defects

NOTES.

1. FABRICATE 12 NOTCHES. ALL NOTCHES TO BE 0.030 ± 0.005 LONG AND 0.0020 ± 0.0005 WIDE WITH DEPTHS AS SHOWN.
3 CIRCUMFERENTIAL NOTCHES ON INSIDE SURFACE 0.0005, 0.0010 AND 0.0015 DEEP AS SHOWN.
3 CIRCUMFERENTIAL NOTCHES ON OUTSIDE SURFACE 0.0005, 0.0010 AND 0.0015 DEEP AS SHOWN.
3 AXIAL NOTCHES ON INSIDE SURFACE 0.0005, 0.0010, 0.0015 DEEP AS SHOWN.
3 AXIAL NOTCHES ON OUTSIDE SURFACE 0.0005, 0.0010, 0.0015 DEEP AS SHOWN
2. AXIAL NOTCHES TO BE PARALLEL TO TUBE CENTER LINE.
3. CIRCUMFERENTIAL NOTCHES TO BE AT RIGHT ANGLES TO TUBE CENTER LINE.
4. BOTTOM OF NOTCHES TO BE FLAT AND CORNERS SQUARE
5. STANDARD Y-14 5 APPLIES

GENERAL NOTES (Unless Otherwise Specified)

- 1 TOLERANCES FRACTIONAL $\pm 1/64$,
DECIMAL ± 0.0002 , ANGULAR $\pm 1^\circ$
- 2 ALL MACHINED SURFACES $16\sqrt{\text{SURFACE}}$
TEXTURE SHALL BE IN ACCORDANCE WITH,
USASI B46 1 (LATEST REV)
- 3 BREAK ALL SHARP EDGES AND REMOVE
ALL BURRS
- 4 ALL MATERIAL SHALL BE AS SPECIFIED
OR APPROVED EQUAL QUALITY

Figure 10. Standard (RDT-E-13-8) for Nondestructive Testing of Stainless Steel Fuel Cladding Tubes

Figure 11. Control Charts - Eddy Current Tester

Table 3. Notch Standard Calibration for Eddy Current Testing (Superior Lot # 42402)				
Notch Position	Tester Response Chart Divisions		Notch Depth (mils)	
	Mean	Range	Kenmar Measured	ARD Measured
Axial ID	4.6 $\pm$ 1.4	3.2 - 6.0	0.60	--
Axial OD	6.9 $\pm$ 2.6	4.3 - 9.5	0.58	0.539
Axial ID	8.3 $\pm$ 1.6	6.7 - 9.9	1.0	--
Axial OD	11.8 $\pm$ 2.9	8.9 - 14.7	0.95	0.901
Axial ID	14.2 $\pm$ 3.7	10.5 - 17.9	1.6	--
Axial OD	20.6 $\pm$ 5.1	15.5 - 25.7	1.55	1.736
Circumferential ID	3.9 $\pm$ 1.1	2.8 - 5.0	0.5	--
Circumferential OD	3.9 $\pm$ 1.2	2.7 - 5.1	0.59	0.582
Circumferential ID	6.6 $\pm$ 1.8	4.8 - 8.4	1	--
Circumferential OD	7.4 $\pm$ 1.8	5.6 - 9.4	1	1.003
Circumferential ID	11.9 $\pm$ 2.7	--	1.6	--
Circumferential OD	11.6 $\pm$ 2.6	--	1.5	1.677

Testing of tubing is then carried out with the standard being transported with each tube. The traces of the standard are then checked to determine that they are within the appropriate control bands prior to acceptance of the traces for the tubes being tested.

A batch of ten tubes which had previously been OD surface defected due to misalignment during air gage testing was eddy current tested. The eddy current traces for the tubing and for the notch standard were analyzed. The pulse height of each defect indication was measured and histograms of number of defects versus pulse heights were constructed for the notch standard and the tubing under test. The histograms for the notch standards are shown in Figures 12, 13, and 14. The histograms for the lot of ten tubes are shown in Figures 15 (total defects) and 16 (defects/foot of tubing). Matching the ten tube histograms with the standard notch histograms indicates that the tube defects give indications corresponding to the following standard notches:

Peak No. 1	1 mil AID 1 mil AOD 1 mil CID	} highest response
Peak No. 2	1/2 mil AOD 1-1/2 mil CID	
Peak No. 3	1 mil AOD 1-1/2 mil AID 1-1/2 mil COD	

Peak No. 4 1-1/2 mil AOD

Where: A = axial
 C = circumferential
 OD = outside surface
 ID = inside surface

Figure 12. 0.5 mil Notch Std Histogram Based on Tubes 1 thru 10 - EC Test 4199-2

Figure 13. 1.0 mil Notch Std Histogram Based on Tubes 1 thru 10 - EC Test

Figure 14. 1.5 mil Notch Std Histogram Based on Tubes 1 thru 10 - EC Test

Visual inspection of the ten tubes was carried out and the defects on the OD of the tubes were matched to the eddy current indications. The histograms of the OD defects are shown in Figures 17 (axial) and 18 (circumferential). Based on these analyses, the OD defect responses correspond to 1 and 1-1/2 mil AOD notches and 1/2 mil COD notches.

The second and third peaks in the COD defect histogram (Figure 18) could not be matched with any of the peaks in the COD notch standard histograms. Therefore, the correlation of these defects with notch depth cannot be made.

All defects not attributable to OD locations were assumed to be ID defects, mid-wall defects, inclusions, local cold work variations, or other perturbations. The histogram for these are shown in Figure 19. These defect responses correspond to 1/2 mil CID, 1 mil CID and AID, and 1-1/2 mil CID and AID.

It must be recognized that the foregoing analysis is intended to compare EC response of naturally occurring defects to responses of notch standards. Exact determination of defect size and orientation must be done visually.

3.5.2 Ultrasonic Testing

The ultrasonic unit has been a continual problem over a considerable period. The problems encountered have been:

1. Malfunction of electronic modules in the Nortec Unit. One module

was returned to the manufacturer four times before the problem (i.e., an incorrectly wired diode) was corrected.

2. Malfunction of the oscilloscope, which was returned to the manufacturer and repaired.
3. Lack of stability in the Tac-Tic in-tank tube transport system. This has been corrected by some design changes to the transducer mountings.
4. Rubber pick-up in the notches in the standard. This has been minimized by replacing the small rubber locating wheels with Teflon wheels.

The initial calibration of the unit was carried out using the notch standard shown in Figure 10. This standard contains a total of 12 notches, composed

Figure 15. Histogram of Total Defects in Tubes 1 thru 10 - EC Test

Figure 18. Histogram of OD Circumferential Defects Located Visually - EC Test

Figure 19. Histogram for Non-OD Defects Located Visually - EC Test

of 1/2, 1, and 1-1/2 mil deep notches in two positions (OD and ID) and in two configurations (axial and circumferential).

The transducer set-up consisted of two transducers in the pulse echo mode, one oriented to detect axial flaws, and the other to detect circumferential flaws. In this mode, difficulty was experienced in detecting the full range of notch depths. For example, when the instrument was tuned to pick up the 1/2 mil notches some of the 1-1/2 mil notch responses were off scale. Detuning to bring the 1-1/2 mil notch responses on scale resulted in loss of the 1/2 mil notch signal. This problem has also been encountered by WADCO,^(a) where an investigation is now in process for determining the possibility of narrowing the range of notch depths to 0.7, 1.0, and 1.3 mils.

^(a) Private communication, R. Lobsinger (WADCO) to K. C. Thomas (ARD) Jan. 1971.

An additional problem with the two transducer set-up is the large variation in signal response with the OD notches. Whereas the range of the ID defect responses is in general within several divisions, the range of the OD defect responses is about 30 divisions. In order to solve these problems, a four transducer pulse-echo method was adopted. All transducers are focused on the tube mid-wall and adjusted as follows:

Transducer	Orientation	Tuning
1	Axial defects	Max. OD response
2	Axial defects	Max. ID response
3	Circumferential defects	Max. OD response
4	Circumferential defects	Max. ID response

Thirty-six runs were made with the notch standard to establish preliminary calibration curves for the unit. The histograms for these 36 runs are shown in Figures 20, 21, and 22. The calibration curves are shown in Figure 23. It should be noted that 1-mil axial OD notch consistently gives a higher defect indication than the corresponding 1-1/2 mil notch. No reason for this discrepancy has been uncovered as the response from this notch in the eddy current test is normal.

The procedure used to UT-test the ten tubes is to obtain maximum response on the transducers as listed previously while maintaining the notch responses within the calibration band. The histograms of the 10-tube lot are shown in Figure 24. Matching the 10-tube lot histogram against the notch standard histograms indicated that the tubes gave UT responses similar to practically all the notch defects in the standard. However, there were strong indications at the 1/2-mil level, particularly at ID locations and possibly the AOD location, and at the AID location at the 1-mil level.

A comparison of the defect correlation by the three methods of analysis are shown in Table 4. It appears from a preliminary examination of these data that the EC method is more sensitive to detecting the OD defects, which were confirmed by visual examination, than is the UT examination. On the other-hand, the UT gave strong indications of ID defects at the lower limit of detection.

Approximately 500 feet of tubing has now been EC and UT tested, and the results are being analyzed. In this second series, additional UT notch standard data are being obtained so that a final UT calibration curve based on approximately 100 test runs will be established.

3.6 EFFECTS OF COLD WORK ON RUPTURE LIFE

Due to a higher priority task no further work was accomplished on the correlation of hardness to cold work as introduced by various manufacturing procedures.

Figure 20. Histogram of 0.5 mil Notch Std Based on 36 UT Runs

Figure 21. Histogram of 1.0 mil Notch Std Based on 36 UT Runs

Figure 22. Histogram of 1.5 mil Notch Std Based on 36 UT Runs

Figure 23. Preliminary Calibration Curve for Ultrasonic Tester Unit Based on 36 Runs

4199-13

Figure 24. Histogram for All Defects Located by UT in Tubes 1 thru 10

Table 4. Correlation of Flaw Detection Methods			
Notch Depth	EC	Visual/EC	UT
1/2 mil	AOD	x	--
	AID	--	--
	COD	--	--
	CID	--	x
1 mil	AOD	x	x
	AID	x	--
	COD	--	--
	CID	x	--
1-1/2 mil	AOD	x	x
	AID	x	--
	COD	x	--
	CID	x	--
x Indication		* Strong indication	

3.7 REPLICA PROCEDURE

A satisfactory procedure has been completed to replicate the ID surface of tube standards up to 16 inches long. The replica material is Chem Sol 4706. The procedure has been revised so that a solid replica of the ID surface is produced. The tube standard is filled with liquid replica material and then resistance heated in the vertical position until cured. The replica is then easily withdrawn by hand.

3.8 REPORTS

All of the test work and measurements planned for the Vacuum Melted Steels Task have been completed except for identification of precipitates by electron probe analysis. A draft of a topical report covering the Vacuum Melted Steel Task and a sub-task on Weldability has been completed.[12]

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