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EVALUATION OF WELDED AND BRAZED STAINLESS STEELS AND SUPERALLOYS IN A CORROSIVE ENVIRONMENT

J. J. O'Connor and P. A. Vozzella

TECHNICAL REPORT AFML-TR-67-258

October 1968

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Air Force Materials Laboratory
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio 45433

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FOREWORD

This Summary Technical Report (Contractor's Reference No. PWA-3138) was prepared by Pratt & Whitney Aircraft, Division of United Aircraft Corporation, East Hartford, Connecticut, as the final report under United States Air Force Contract No. AF33(615)-5129, as amended by SA3(68-1825), dated 16 February 1968. This Contract was initiated under Project 7381, "Materials Applications", Task 738107, "Detection, Prevention and Control of Corrosion". The work was administered by the Air Force Materials Laboratory, Air Force Systems Command, USAF, with Mr. George M. Yoder as Project Monitor.

This report covers work conducted from 1 June 1966 through 1 July 1968.

The authors were associated with the Contract work in the following capacities: J. J. O'Connor, as Assistant Project Engineer, was Program Manager and P. A. Vozzella was the responsible Metallurgical Engineer. Other personnel associated with the conduct of the program were R. A. Doak, Project Engineer; P. Grande, Project Metallurgist; and R. Muszynski, Non-Destructive-Test Senior Engineer.

This technical report has been reviewed and is approved.

D. A. SHINN, Chief
Aeronautical Systems Support Branch
Materials Support Division
AF Materials Laboratory

ABSTRACT

Temperature-cycling tests were conducted on specimens of ten alloys representative of materials in current use in high-speed aircraft. Half of the specimens were welded and half were of one-piece construction with a braze-material patch. All specimens, with the exception of some controls, had salt patches extending over the welded or brazed regions. The specimens were tested under constant load during temperature cycling. The test conditions were such as could result in corrosion and consequent degradation of mechanical properties of the alloys. Subsequent to environmental exposure, room-temperature tensile tests were performed, to determine the degree of alloy deterioration. Nondestructive methods of inspection were evaluated and found to be ineffective for detecting the incipient corrosion which was encountered. Analyses of the environmental-test data were conducted and the relative influence of combinations of exposure conditions on the production of corrosion in specimens was ascertained. Design limits are presented for all the materials which were investigated. It was not possible in this program to evaluate the capability of welding or brazing for restoring the mechanical properties of alloys after such properties have been degraded by corrosion. Recommendations are made as to the directions which any further investigations into the corrosion phenomenon should take.

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EVALUATION OF WELDED AND BRAZED STAINLESS STEELS AND SUPERALLOYS IN A CORROSIVE ENVIRONMENT

I

INTRODUCTION

Welding and brazing of subsonic-aircraft metal structural members and engine components, both as means of fabrication and as methods for repair of damaged or worn parts, are techniques which were long ago proved acceptable by extensive laboratory and flight experience under realistic environmental conditions for such aircraft. When aircraft with Mach-3 capability were designed, the designers, in their selection of materials, necessarily relied heavily on the subsonic- and low-supersonic-aircraft experience. This was because very few evaluations of welded and brazed materials had been made under controlled laboratory conditions which simulated environmental conditions featuring marine atmospheres, high stresses, and elevated temperatures, such as Mach-3-aircraft components were expected to encounter.

Although Mach-3 aircraft have seen some service, very little flight time has thus far been logged, and the very limited quantity of data which has been obtained on the serviceability of welded and brazed stainless-steel and superalloy components has been characterized by very wide scatter. The data have clearly been insufficient to establish reliability and substantiate theory pertaining to structural capabilities of such components when subjected to severe operating conditions.

The United States Air Force Systems Command felt that the behavior of welded and brazed stainless steels and superalloys, of the types used in Mach-3 aircraft and aircraft engines, should be investigated under simulated marine-type environmental conditions while being exposed to elevated temperatures and severe stresses. The data obtained from such an investigation would be useful in establishing the reliable service lives for components fabricated or repaired by the joining methods under discussion.

The Contract provided that the primary objective of the program was to determine if welding and brazing have any detrimental effects on the strength and corrosion-resistance properties of certain alloys specified therein after prolonged periods of exposure to extremely adverse environmental conditions. The extent of any degradation of the specimens' mechanical properties was to be measured and means for detecting non-destructively any defects resulting from the exposure were to be evaluated. This summary technical report reviews the Contractor's work under the Contract and discusses the results obtained from conducting the environmental-test program.

II

MATERIAL SELECTION

Ten alloys, of the types currently in use in Mach-3 aircraft and aircraft engines, were investigated. Their designations and chemical compositions are presented in Table I and their mechanical-properties acceptance data are presented in Table II.

Representative applications of the ten alloys are listed in Table III. The materials are used primarily in regions of airframe or power plant where high stresses and/or severe temperatures prevail under operating conditions for supersonic aircraft.

All of the materials were procured as annealed sheet-stock. The condition of each alloy prior to its being welded or brazed is indicated in Table IV.

TABLE I

DESIGNATIONS, SOURCES, HEAT CODES, THICKNESSES, AND CHEMICAL COMPOSITIONS OF MATERIALS USED FOR ENVIRONMENTAL-TEST SPECIMENS

			Heat Code			CHEMICAL ANALYSIS																				
Material	Source	Use*	Supplier	P&WA	Thickness (in)	C	P	S	Si	Mn	Ni	Cr	W	Sn	Zr	Cu	Al	Fe	Co	Mo	V	Ti	B	N	H	ThO2
AM 350	Universal Cyclops	W	-	M5471	0.102	0.10	0.019	0.003	0.26	0.98	4.15	16.74						bal.		2.76				0.120		
AM 350	Allegheny Ludlum	B	79739	-	0.055	0.095	0.020	0.012	0.30	0.93	4.33	16.34						bal.		2.73				0.092		
AM 355	Carpenter Steel	WB	72427	-	0.090	0.14	0.019	0.011	0.37	0.90	4.31	15.56						bal.		2.77	0.05			0.102		
PH15-7Mo	Continental Metals	W	890683	-	0.093	0.070	0.019	0.011	0.42	0.53	7.10	15.14					1.13	bal.		2.21						
PH15-7Mo	Continental Metals	B	880362	-	0.062	0.068	0.020	0.016	0.30	0.62	7.16	15.20					1.14	bal.		2.55						
PH14-8Mo	ARMCO Steel	WB	-	M4167	0.062	0.05	0.003	0.007	0.43	0.46	8.03	13.56					1.14	bal.		2.26						
Hastelloy X	Union Carbide	W	260-5-4852	YCCH	0.085/0.093	0.06	0.016	0.003	0.66	0.63	bal.	22.13	0.55					17.94	1.00	9.01						
Hastelloy X	Union Carbide	B	260-5-4497	YCFK	0.056/0.062	0.08	0.011	0.005	0.64	0.69	bal.	21.68	0.59					19.20	1.95	8.92						
René 41	Eastern Stainless Steel	W	E96043	-	0.085	0.049		0.005	0.04	0.03	bal.	19.16					1.55	0.30	11.60	9.25		3.25	0.006			
René 41	Eastern Stainless Steel	B	E96092	-	0.057/0.063	0.048		0.007	0.03	0.02	bal.	19.42					1.57	0.20	10.90	9.45		3.30	0.005			
Udimet 700	Eastern Stainless Steel	WB	71765	BRSA	0.071/0.078	0.07			<0.01	0.10	bal.	14.90			<0.06	<0.10	3.96	0.17	17.10	5.40		3.59	0.023			
A 286	Eastern Stainless Steel	W	W22344	HNFZ	0.085/0.090	0.046	0.020	0.014	0.65		25.99	15.35	1.45				nil	bal.		1.34	0.15	2.14	0.006			
A 286	Continental Metals	B	50591	INYH	0.056/0.060	0.06	0.009	0.003	0.62		24.26	14.72	1.54				0.13	bal.		1.29	0.32	1.94	0.005			
Greek Ascoloy	Edgcomb Steel	W	7555	IJAN	0.093	0.19	0.012	0.025	0.42	0.33	1.94	12.93	2.60	0.012		0.09	<0.01	bal.		0.04						
Greek Ascoloy	Eastern Stainless Steel	B	-	HGTS	0.056/0.062	0.14			0.29	0.37	2.01	13.35	2.60	<0.05		<0.10	<0.05	bal.		0.12						
TD Nickel	E.I. DuPont	W	Lot 920	-	0.075	0.019		0.001			bal.	<0.01						<0.01	<0.01			<0.021		<5 ppm	1 ppm	2.16
TD Nickel	E.I. DuPont	B	-	M8546	0.076/0.079	0.021		0.002				<0.003				<0.01		<0.03	<0.05			<0.05				2.32

*B - Brazed Specimens; W - Welded Specimens

TABLE II

MATERIAL ACCEPTANCE DATA

				Solution - Heat - Treated - Tensile Data						Fully Heat - Treated - Tensile Data						Stress Rupture				Creep		
Material	AMS Spec.	PWA Spec.	Heat Code	Temp (F)	UTS (ksi)	0.2% YS (ksi)	El (%)	RA (%)	Hardness	Temp (F)	UTS (ksi)	0.2% YS (ksi)	El (%)	RA (%)	Hardness	Temp (F)	Stress (ksi)	Rupture Life (Hrs)	El (%)	Temp (F)	Stress (ksi)	Time to 0.1% Creep (Hrs)
[illegible]	[illegible]	-	Spec. Requirements	70	143 (max)	40 (max)	20 (min)	-	Rc 25 (max)	70	185 (min)	150 (min)	19 (min)	-	Rc 42-50							
			M 6474	70	159	60	30	-	Rc 19	70	221	160	13	-	Rc 49							
			79139	70	166	76	30	-	Rc 24	70	217	194	11	-	Rc 49							
AM 355	5547 B	-	Spec. Requirements	-	-	-	-	-	Rc 25 (max)	70	143 (min)	140 (min)	10 (min)	-	Rc 37-44							
			78427	-	-	-	-	-	Rc 41	70	195	162	14	-	Rc 44							
PH15-7Mo	5520 A	-	Spec. Requirements	70	130 (max)	65 (max)	25 (min)	-	Rb 100 (max)	70	225 (min)	200 (min)	4 (min)	-	Rc 46 (min)							
			49653	70	135	64	32	-	Rb 92	70	212	210	6	-	Rc 45							
			89382	70	140	60	30	-	Rb 91	70	197	170	6	-	Rc 40							
PH14-8Mo	-	-	Spec. Requirements*	-	-	-	-	-	-	70	220 (min)	190 (min)	4 (min)	-	Rc 45 (min)							
			M 9157	-	-	-	-	-	-	70	226	200	9	-	Rc 49							
Hastelloy X	5536 E	-	Spec. Requirements	-	-	-	-	-	-	70	100 (min)	45 (min)	35 (min)	-	-	1500	15	24 (min)	8 (min)			
			YCCH	-	-	-	-	-	-	70	113	57	44	-	-	1500	15	56	49			
			YCFK	-	-	-	-	-	-	70	109	56	43	-	-	1500	15	72	31			
René 41	5545	-	Spec. Requirements	70	170 (max)	140 (max)	30 (min)	-	Rc 30 (max)	70	170 (min)	130 (min)	10 (min)	-	Rc 35 (min)							
			Spec. Requirements	-	-	-	-	-	-	1400	140 (min)	110 (min)	3 (min)	-	-							
			E 96643	70	165	95	40	-	Rc 29	70	200	165	20	-	Rc 44							
										1400	142	132	12	-	Rc 46							
			E 96692	70	137	69	44	-	Rc 18	70	206	176	22	-	Rc 43							
										1400	140	131	4	-	Rc 45							
Udimet 700	-	1013	Spec. Requirements	-	-	-	-	-	-	70	185 (min)	140 (min)	16 (min)	15 min	Rc 34-42	1400	85	30 (min)	-	1300	74	150 (min)
			Spec. Requirements	-	-	-	-	-	-	1400	150 (min)	125 (min)	20 (min)	26 min	-							
			BRSA	-	-	-	-	-	-	70	205	144	19	-	Rc 40	1400	85	10	3	1300	74	>226
			BRSA	-	-	-	-	-	-	1400	153	132	12	-	-							
A-286	5525 B	-	Spec. Requirements	70	105 (max)	-	53 (min)	-	Rb 88 (max)	70	140 (min)	95 (min)	15 (min)	-	Rc 24-35	1200	62.5	24 (min)				
			HNFZ	70	91	-	48	-	Rb 81	70	152	117	29	-	Rc 33	1200	62.5	>24				
			INYH	70	95	38	46	-	Rb 79	70	153	111	21	-	Rc 31	1200	62.5	>25				
Greek Ascoloy	5616 A	-	Spec. Requirements	70	130 (max)	-	18 (min)	-	-	-	-	-	-	-	Rc 32 (min)							
			LIAN	70	142	112	13	-	Rc 26	-	-	-		-	Rc 32							
			HGTS	70	133	-	14	-	Rc 24	-	-	-	-	-	Rc 44							
TD Nickel	-	1003	Spec. Requirements	-	-	-	-	-	-	70	40 (min)	44 (min)	10 (min)	-	-	2000	5.5	20 (min)				
			Spec. Requirements	-	-	-	-	-	-	2000	12 (min)	9.5 (min)	2 (min)	-	-							
			Lot 920	-	-	-	-	-	-	70	46	41	19	-	Rb 44	2000	3.3	>20				
			Lot 920	-	-	-	-	-	-	2000	13	12	3	-	-							
			M 9346	-	-	-	-	-	-			Not Available										

* DMIC Report No. 223

TABLE III

REPRESENTATIVE APPLICATIONS FOR MATERIALS
INVESTIGATED IN CORROSION PROGRAM

Material	Representative Applications in Supersonic Aircraft
AM 350 AM355 PH15-7Mo PH14-8Mo	Airframe and engine structural members requiring high strength and high corrosion resistance
Hastelloy X	Engine structural members in burner and turbine sections
René 41	Engine structural members in high-pressure-compressor and diffuser sections
Udimet 700	Turbine blades
A 286	Structural members; turbine discs
Greek Ascoloy	Compressor blades and vanes; turbine discs
TD Nickel	Experimental burner hardware; turbine vanes

TABLE IV

MATERIAL CONDITION PRIOR TO WELDING AND BRAZING

Material	Condition
AM 350	1900F solution anneal
AM 355	1900F solution anneal
PH15-7Mo	1950F solution anneal
PH14-8Mo	1850F solution anneal
Hastelloy X	2150F solution anneal
René 41	1975F solution heat treat
Udimet 700	2150F solution anneal
A 286	1800F solution heat treat
Greek Ascoloy	Annealed
TD Nickel	2000F stress-relieved

III

TEST-SPECIMEN DESIGN AND FABRICATION

Salt-coated welded and brazed joints of the ten materials discussed in Section II were evaluated in the form of specimens subjected to laboratory testing under the controlled steady-state loading and cyclic-temperature conditions which are described in Section V. The configurations of the welded and brazed specimens were identical, except, of course, in the regions of weld and braze application. Discussions of the specimen geometry, the process controls utilized, the initial and intermediate inspection methods, and the post-processing heat treatments follow.

A. Welded Specimens

The welded specimens were prepared by first cutting strips of each material from sheet. Strips of the same material were then paired and the members of a pair butt-welded together along one edge to form a panel. The only exception to this procedure applied to the TD-Nickel strips. These were machined to have mating edges of the double-"V"-groove type, with 0.020-to-0.030-inch lands, so that the heat input to the metal during joining would be as low as possible and melting of parent metal would be minimized. TD Nickel is a thoria-dispersion-strengthened alloy and therefore quite difficult to weld since the thoria particles are essentially insoluble in the matrix. Should significant amounts of parent metal be melted during welding, the thoria dispersoid would agglomerate extensively, causing severe reduction of the material's mechanical strength.

The welding operation was performed on an automatic welding machine utilizing the tungsten-inert-gas (TIG) process. The machine is shown in the photograph, Figure 1. Where a filler was necessary, parent metal was used for all alloys except TD Nickel. Waspaloy, an alloy characterized by high strength at elevated temperatures and a melting point lower than TD Nickel, was selected as the filler for TD-Nickel welds, since, as previously mentioned, it was considered to be most important to minimize parent-metal melting and thus maintain material strength. All welds were oriented ninety degrees to the direction in which the sheet had been rolled. The weld schedules are shown in Table V and a representative welded panel is shown in Figure 2.

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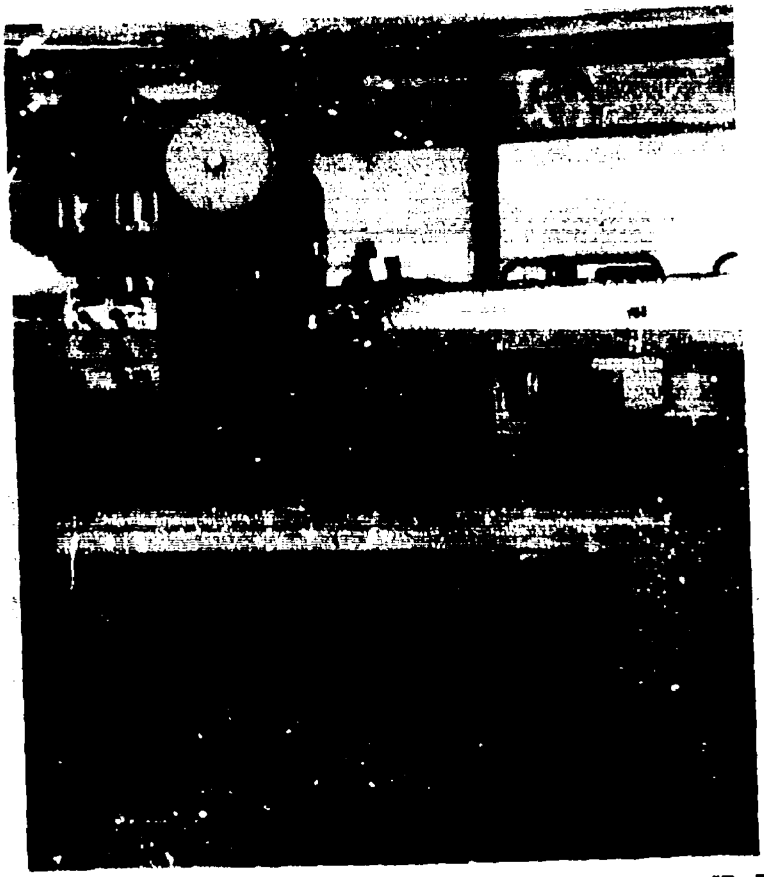

Figure 1 TIG Automatic Welding Machine (XP-71169)

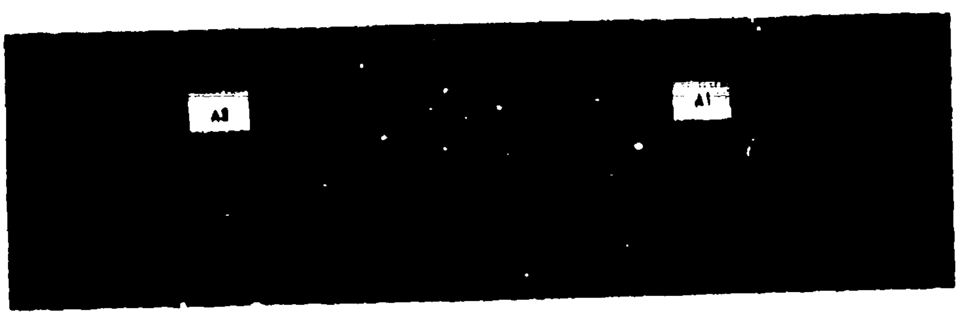

Figure 2 AM-355 Welded Sheet (XP-71168)

After welding, all joints were X-rayed using radiographic techniques which were capable of producing a penetrameter sensitivity of at least two per cent. Only joints which had no significant radiographic indications (aircraft-quality-weld standards) were accepted. Acceptable panels were heat-treated in accordance with the schedules shown in Table V, ground to have uniform thickness as close as possible to one-sixteenth inch, and reinspected radiographically; the grinding operation was necessary in order to enable accurate computation of imposed stresses for the environmental testing and of mechanical properties following that testing.

TABLE V

WELDING PARAMETERS AND POST-WELD HEAT TREATMENTS OF WELD-TEST SPECIMENS

Material	Amps	Volts	Weld Speed (in./min)	Electrode Dia (in.)	Back-Up Gas	Torch Gas	Post-Weld Heat Treatment
AM 350	75	10.7	10	3/32	Argon	Helium	30 min. at 1710F conditioning 3 hrs. at -100F transformation 3 hrs. at 850F temper
AM 355	45	13.5	10	3/32	Argon	Helium	30 min. at 1710F conditioning 3 hrs. at -100F transformation 3 hrs. at 1000F temper
PH15-7Mo	40	15	0.25	3/32	Argon	Helium	10 min. at 1750F conditioning 8 hrs. at -100F transformation 1 hr. at 1050F temper
PH14-8Mo	40	13.5	10	3/32	Argon	Helium	1-1/2 hr. at 1700F conditioning 8 hrs. at -100F transformation 1-1/2 hrs. at 950F temper
Hastelloy X	75	11	10	3/32	Argon	Helium	None
René 41	30	14	5	3/32	Argon	Helium	16 hrs. at 1400F precipitation treatment
Udimet 700	70	8	10	1/16	Argon	Argon	4 hrs. at 1975F solution treatment 4 hrs. at 1550F stabilization 16 hrs. at 1400F precipitation treatment
A 286	50	13	11	3/32	Argon	Helium	16 hrs. at 1325F precipitation treatment
Greek Ascoloy	80	9.5	11	3/32	Argon	Helium	1/2 hr. at 1800F austenitize 2 hrs. at 1050F temper
TD Nickel	*	6.5	17	3/32	Argon	Argon	2 hrs. at 1975F solution 4 hrs. at 1550F stabilization 16 hrs. at 1400F precipitation (Heat treatment necessary for Waspaloy filler)

*Waspaloy filler wire used. Two passes were made: the first at 140 amps with 25-inches-per-minute wire feed; the second at 155 amps with 32-inches-per-minute wire feed.

The last two steps taken in preparing welded specimens for the environmental test program were the machining of each panel into several specimens with the configuration shown by the top sketch in Figure 3, and a final pre-environmental-test inspection of the finished specimens. A photograph of a typical welded specimen appears in Figure 4.

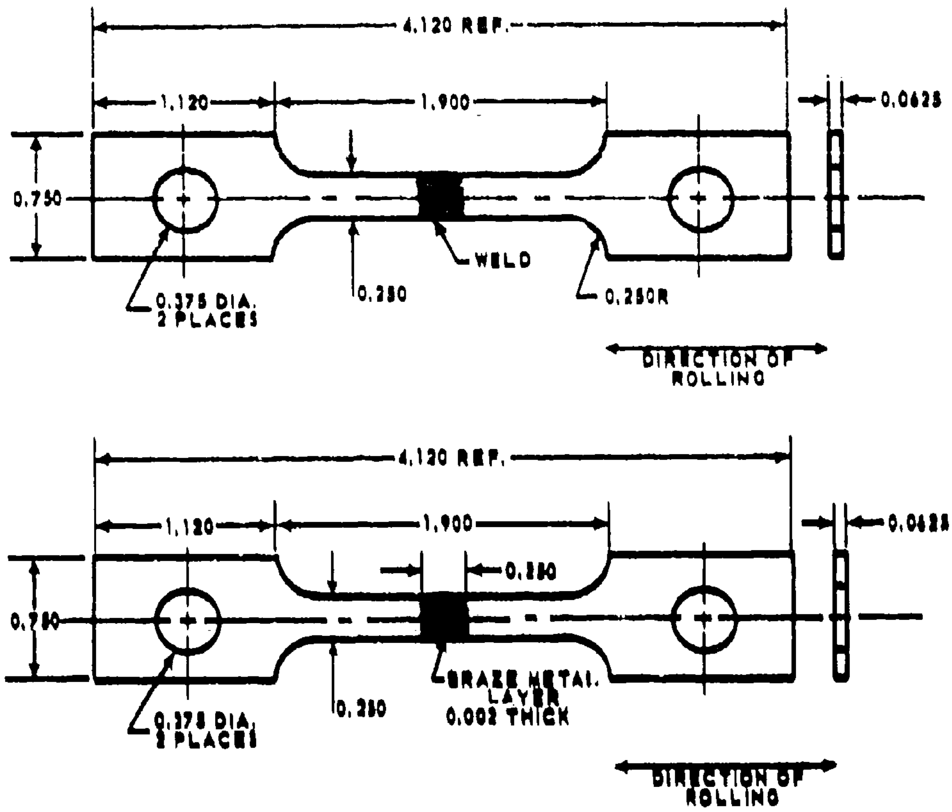

Figure 3 Designs of Welded (upper) and Brazed (lower) Test Specimens (67-258-1)

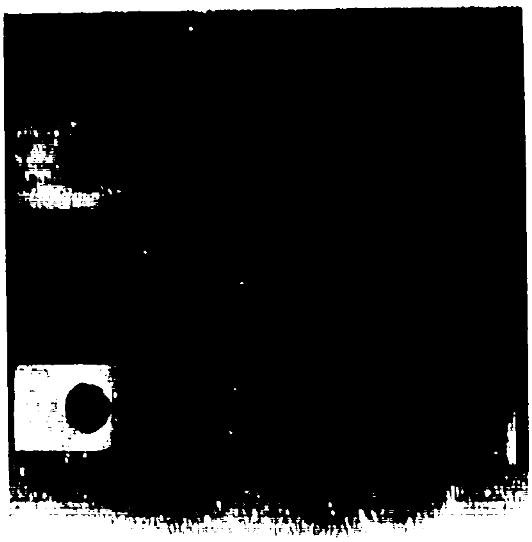

Figure 4 Representative Welded, Brazed, and Salt-Coated Specimens (H-01360)

B. Brazed Specimens

Whereas the welded specimens were fabricated from panels formed by welding two strips of a given material together, the brazed specimens were of one piece, with a layer of braze alloy superimposed, as shown by the lower sketch in Figure 3 and in the photograph, Figure 4. Dimensionally, the two types of specimens were indistinguishable, except that for brazed specimens, the width of the braze layer was controlled to be approximately one-quarter inch and the thickness held to 0.002-0.005 inch by grinding. Because the purpose of the environmental-test program was to determine if the exposure of joint specimens was detrimental to the mechanical properties of the parent metal and not to ascertain if there was impairment of joint strength, the absence of an actual joint, such as the welded specimens had, was deemed to be of no consequence. It was considered that the metallurgical interactions of the braze alloys with the base metals would be at least as reliably evaluated when a braze coating alone was used, as they would be were an actual brazed joint to be used. Furthermore, absence of such a joint would facilitate more accurate determination of base-metal stresses. All braze specimens were cleaned mechanically and chemically before braze application, in order to ensure satisfactory bonding.

Table VI identifies the braze alloys and temperatures used in the specimen-fabrication program. The braze alloys selected for the various materials were, in general, representative of those being utilized in the fabrication of aerospace components at the time of the Contract. Their strengths and resistances to oxidation were compatible with requirements set by the expected normal operating temperatures of the base metals. However, for René-41 and Udimet-700 specimens, a special boron-free braze alloy was employed, in order to avoid the problem of boron embrittlement. This alloy, referred to as J8600, did require the use of a braze temperature which was slightly high for the two base materials, but, by using relatively short brazing cycles, it was possible to reduce the likelihood of any strength impairment.

TABLE VI

BRAZE-ALLOY COMPOSITIONS AND BRAZING TEMPERATURES

Braze Alloy	Composition	Braze Temperature (F)
AMS 4776	71.7 Ni-4Si-16.5Cr-4Fe-3.8B	2150
PWA 705	62.5Ag-32.5Cu-5Ni	1710
PWA 707	56Ag-42Cu-2Ni	1750
J8600	38Ni-33Cr-4Si-25Pd	2150
Au-Ni	82Au-18Ni	1800

The brazing parameters used are set forth in Table VII. For those materials the compositions of which contained significant amounts of strong oxide formers (aluminum and titanium), a relatively high vacuum was maintained (less than two microns of mercury). A dry hydrogen atmosphere (-40F dew point or better) was used for the other materials.

The post-braze heat-treatment schedules for specimens of each material appear in the last column of Table VII. The brazing temperatures involved were compatible with the required heat treatments for the various materials.

All brazed specimens were inspected subsequent to machining and again after post-braze heat treatment.

TABLE VII

BRAZING TECHNIQUES AND POST-BRAZE HEAT TREATMENTS OF BRAZE-TEST SPECIMENS

Material	Braze Alloy	Braze Temperature*	Braze Environment	Post-Braze Heat Treatment
AM 350	PWA 705	1710F	Hydrogen	3 hrs. at -100F transformation 3 hrs. at 850F temper
AM 355	PWA 705	1710F	Hydrogen	3 hrs. at -100F transformation 3 hrs. at 1000F temper
PH15-7Mo	PWA 707	1750F	Vacuum	8 hrs. at -100F transformation 1 hr. at 1050F temper
PH14-8Mo	PWA 705	1700F	Vacuum	8 hrs. at -100F transformation 1-1/2 hrs. at 950F temper
Hastelloy X	AMS 4776	2150F	Hydrogen	None
René 41	J8600	2150F	Vacuum	16 hrs. at 1400F precipitation treatment
Udimet 700	J8600	2150F	Vacuum	4 hrs. at 1975F solution treatment 4 hrs. at 1550F stabilization 16 hrs. at 1400F precipitation treatment
A 286	Au-Ni	1800F	Vacuum	16 hrs. at 1325F precipitation treatment
Greek Ascoloy	Au-Ni	1800F	Hydrogen	2 hrs. at 1050F temper
TD Nickel	AMS 4776	2150F	Hydrogen	None

*The time at temperature for each brazing cycle was approximately 10 minutes

IV

INVESTIGATION OF NON-DESTRUCTIVE-TEST METHODS

The Contract required that, in addition to using destructive-testing procedures (such as tensile tests) for evaluating the extent of degradation in the mechanical properties of the several materials, resulting from the environmental testing, non-destructive testing should be used in the evaluations. It provided further that a maximum of eighty non-destructive-test specimens (four for each material and for each process) were to be used in the investigation.

It was considered desirable to be able to predict, with assurance of reasonable accuracy, when a structural member of an airframe or engine exposed to severe environmental conditions, including a sea-salt atmosphere, would experience degradation of its mechanical properties. If this goal were realized, then weakened parts could be replaced or strengthened by repair on the basis of a non-destructive-testing schedule before a failure occurred. Radiographic examination is a technique commonly used for crack detection. It was used extensively in the program. However, it has only modest reliability for disclosing minute crack indications and practically no reliability at all for determining incipient cracking. In addition to radiographic examination (penetrameter sensitivity of two per cent), fluorescent-penetrant inspection (ZL30) and other non-destructive-test techniques were investigated in the program in an effort to establish reliable degradation-prediction methods. The other non-destructive-test techniques are discussed herein.

A. Crack Determination

Non-destructive testing of the welded and brazed specimens included use of a method for detecting cracks and two methods for sensing corrosion. Using the methods employed for detecting evidence of corrosion in the non-destructive-testing program, it was not possible to resolve discrepancies the depths of which were less than approximately 0.005 inch.

The method selected for cracks was pulse-echo angle-beam ultrasonics. The initial step taken in order to make use of this method was to establish the optimum ultrasonic wave-frequency and beam-angle parameters for each of the ten alloys. For the purposes of the investigation, cracks were simulated by scratches made on the material samples. Optimum pulse frequencies were determined by using one-half-inch-diameter transducers with different output ranges. Optimum beam angles were ascertained by means of Lucite wedges attached to the transducers. The ultrasonic instrument used was a Branson 301 Sonoray with 2.25-, 3.5-, 5-, and 7-megacycle transducers. This instrument is shown in Figure 5.

TABLE VIII

OPTIMUM BEAM ANGLES FOR USE IN ULTRASONIC
INSPECTION OF ALLOY SPECIMENS

Material	Beam Angle
AM 350	28°
AM 355	28°
PH15-7Mo	28°
PH14-8Mo	28°
Hastelloy X	30°
René 41	26°
Udimet 700	36°
A 286	30°
Greek Ascoloy	26°
TD Nickel	30°

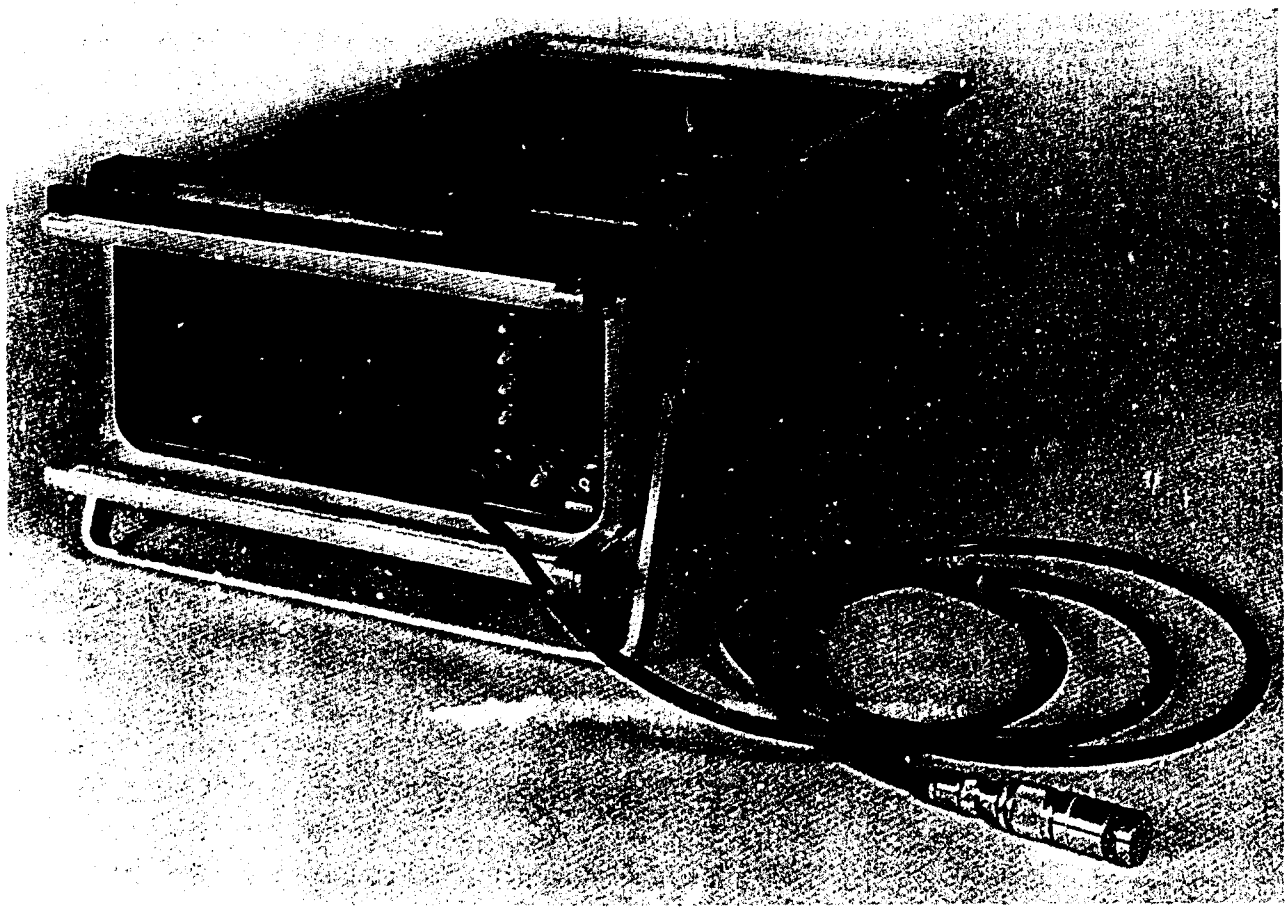

Figure 5 Branson 301 Sonoray Used in Investigation of Non-Destructive-Test Methods (ultrasonic) (XP-60743)

Table VIII lists the optimum beam angles found for each material, and Figures 6 through 15 are plots of the data in the form of families of curves indicating the frequencies which resulted in the maximum responses. It will be observed that the optimum beam angles ranged from 26° to 36°, and the optimum responses occurred when a transducer with output characteristics centered at 3.5 megacycles was used. The families of curves are similar for all of the investigated materials.

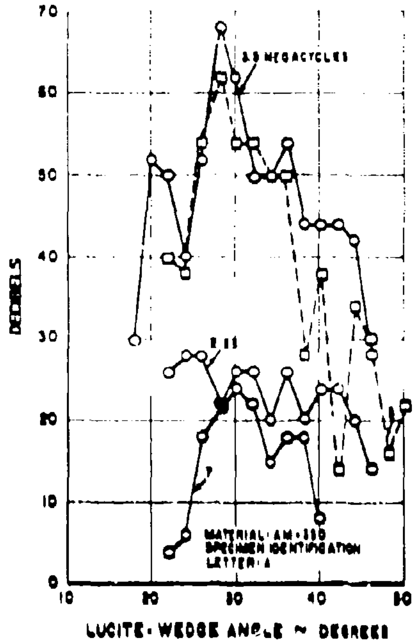

Figure 6   Maximum Decibels Reflected v. Transducer Frequency and Lucite-Wedge Angle. Ultrasonic Testing of AM 350   (H-71014)

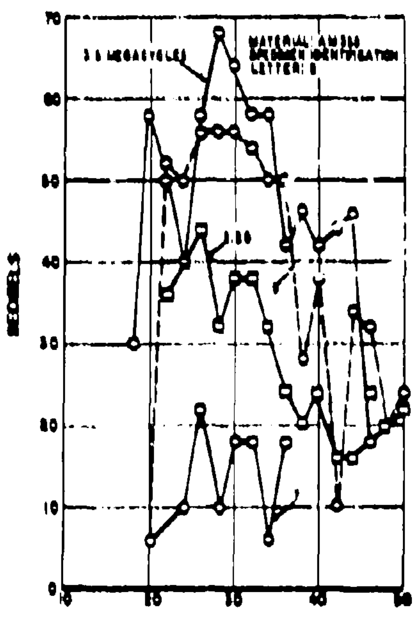

Figure 7   Maximum Decibels Reflected v. Transducer Frequency and Lucite-Wedge Angle. Ultrasonic Testing of AM 355   (H-71010)

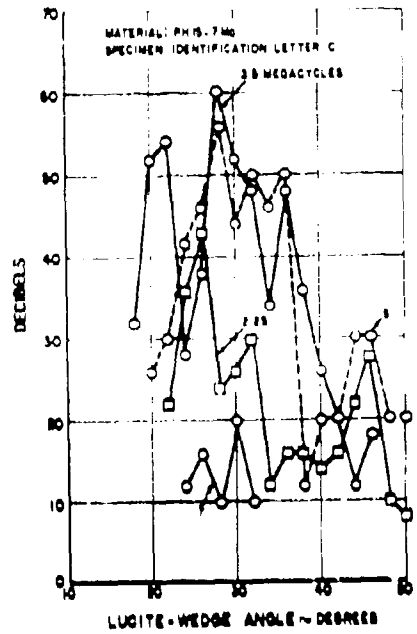

Figure 8 Maximum Decibels Reflected v. Transducer Frequency and Lucite-Wedge Angle. Ultrasonic Testing of PH15 - 7Mo (H-71006)

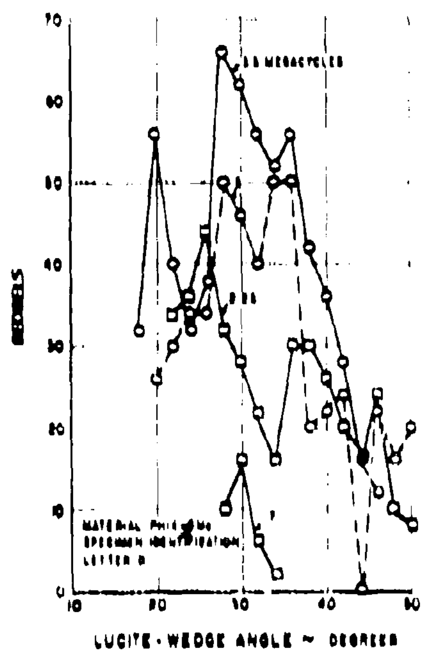

Figure 9 Maximum Decibels Reflected v. Transducer Frequency and Lucite-Wedge Angle. Ultrasonic Testing of PH14 - 8Mo (H-71015)

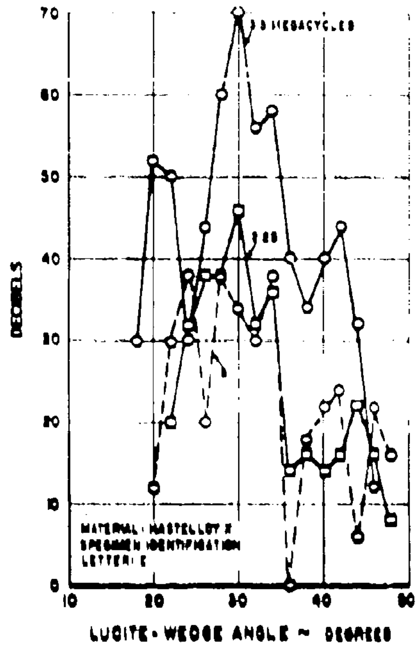

Figure 10 Maximum Decibels Reflected v. Transducer Frequency and Lucite-Wedge Angle. Ultrasonic Testing of Hastelloy X (H-71011)

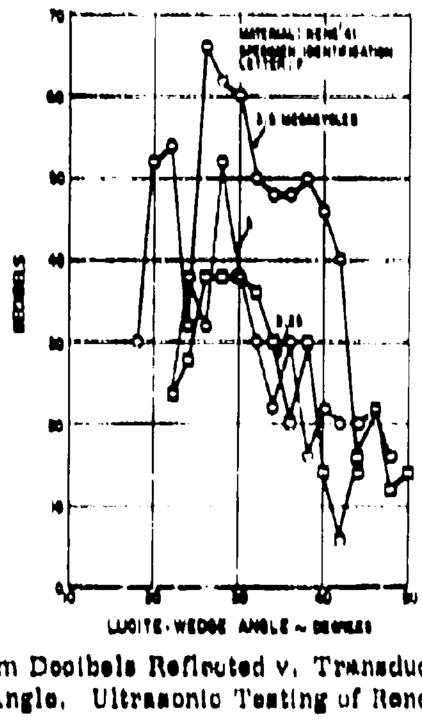

Figure 11 Maximum Decibels Reflected v. Transducer Frequency and Lucite-Wedge Angle. Ultrasonic Testing of René 41 (H-71007)

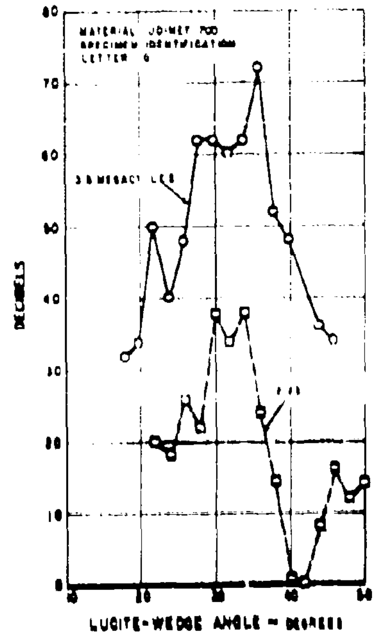

Figure 12 Maximum Decibels Reflected v. Transducer Frequency and Lucite-Wedge Angle. Ultrasonic Testing of Udimet 700 (H-71012)

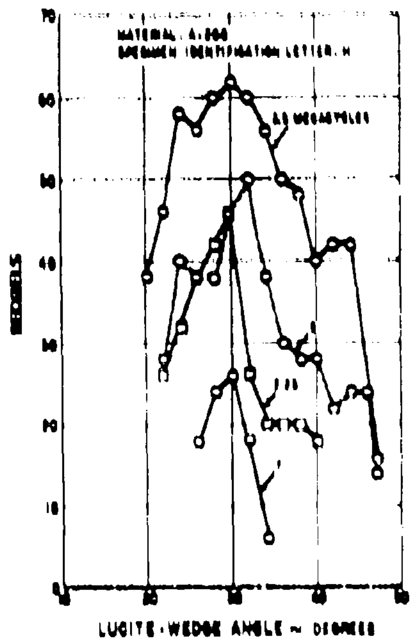

Figure 13 Maximum Decibels Reflected v. Transducer Frequency and Lucite-Wedge Angle. Ultrasonic Testing of A 286 (H-71008)

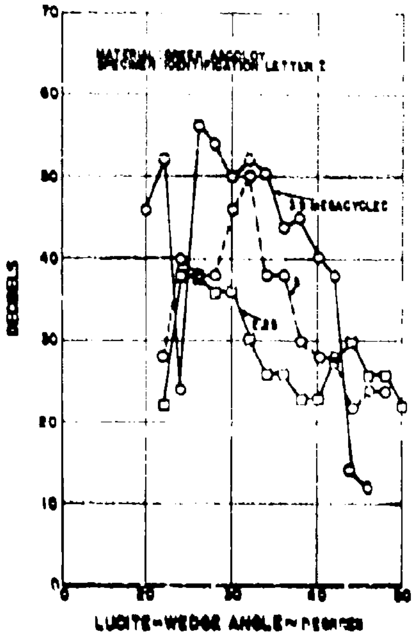

Figure 14 Maximum Decibels Reflected v. Transducer Frequency and Lucite-Wedge Angle. Ultrasonic Testing of Greek Ascoloy (H-71009)

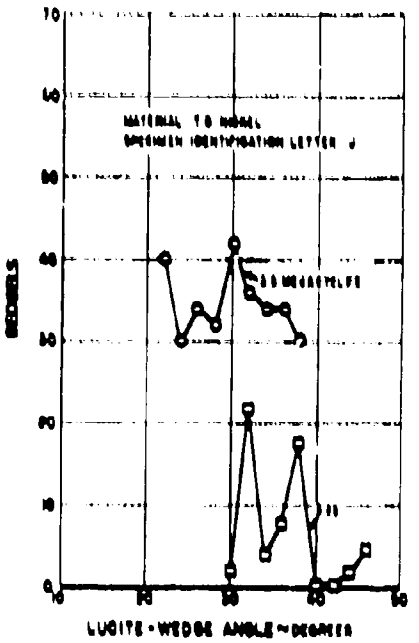

Figure 15 Maximum Decibels Reflected v. Transducer Frequency and Lucite-Wedge Angle. Ultrasonic Testing of TD Nickel (H-71018)

With the use of the optimum parametric values obtained in the preliminary investigation, pre-environmental-test ultrasonic inspections were conducted on each specimen in order to establish base response characteristics for comparison with post-environmental-test ultrasonic-inspection data. It was expected that a discrepancy in the specimen would change the response signal and show up on the screen as a pip.

B. Corrosion Detection

The methods which were investigated for the purpose of detecting corrosion of the welded and brazed specimens were beta-ray-backscatter and electrical-conductivity measurements. The theory behind the employment of these two methods was that the presence of corrosion would so change the internal structure of the materials in the welded and brazed regions that beta-ray count and electrical conductivity would be measurably affected. It was hoped that by making these measurements before and after environmental testing, and by considering the data thus obtained in conjunction with the findings from mechanical testing, it might be possible to determine the presence and extent of mechanical-property degradation resulting from corrosion effects within a joint without the necessity for destroying the specimen. Reliable correlations between changes from pre-use values with deterioration in strength might thus be established for actual welded and brazed components of airframes and engines, and the need for repair or replacement could be anticipated without awaiting failure of a part.

The pre-environmental-test data obtained for specimens of each of the ten materials by the beta-ray-backscatter method are presented in Table IX. The beta-ray instrument used was a Micro-derm with a carbon-14 source, shown in Figure 16. Pre-test conductivities for specimens of the four nonmagnetic materials are also given in the table. The conductivities were obtained by the eddy-current method of measurement, utilizing an FM 100-Series Magnatest conductivity meter, shown in Figure 17. Magnetic materials could not be inspected by this method because their magnetic fields would override the eddy currents.

TABLE IX

PRE-ENVIRONMENTAL-TEST BETA-RAY-BACKSCATTER AND ELECTRICAL-CONDUCTIVITY DATA FOR ALLOY SPECIMENS

	Dial Reading*		Conductivity (% IACS)**	
Specimen Material	Welded Specimens	Brazed Specimens	Range for Welded Specimens	Range for Brazed Specimens
AM 350	324 - 326	323 - 326	---	---
AM 355	323 - 328	320 - 329	---	---
PH15-7Mo	331 - 340	337 - 341	---	---
PH14-8Mo	326 - 327	324 - 328	---	---
Hastelloy X	263 - 264	298 - 303	1.33 - 1.35	1.42 - 1.43
René 41	273 - 285	---	1.26 - 1.30	1.25 - 1.42
Udimet 700	289 - 293	345 - 346	1.30 - 1.32	1.28 - 1.29
A 286	305 - 308	---	1.76 - 1.77	1.83 - 1.84
Greek Ascoloy	296 - 306	332 - 335	---	---
TD Nickel	260 - 265	261 - 272	---	---

*Microderm meter and source calibration:

Dial reading of 200 is equivalent to 38,000 electron counts per minute
Dial reading of 600 is equivalent to 15,500 electron counts per minute
Linear relationship

**Conductivities are expressed as percentages relative to conductivity of copper taken as 100 percent (International Annealed Copper Standards).

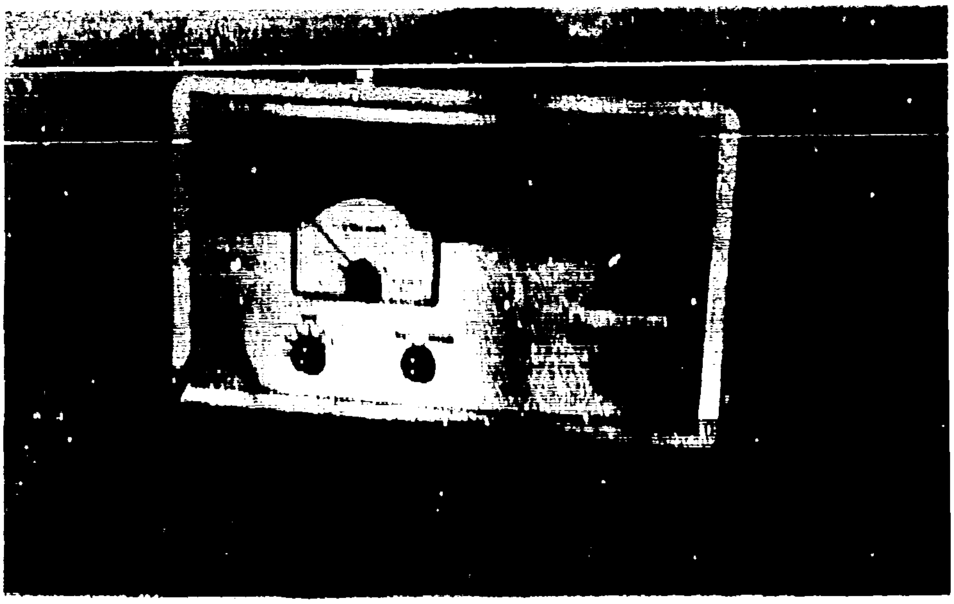

Figure 16 Micro-derm Used in Investigation of Non-Destructive Test Methods (beta-ray backscatter) (XP-00748)

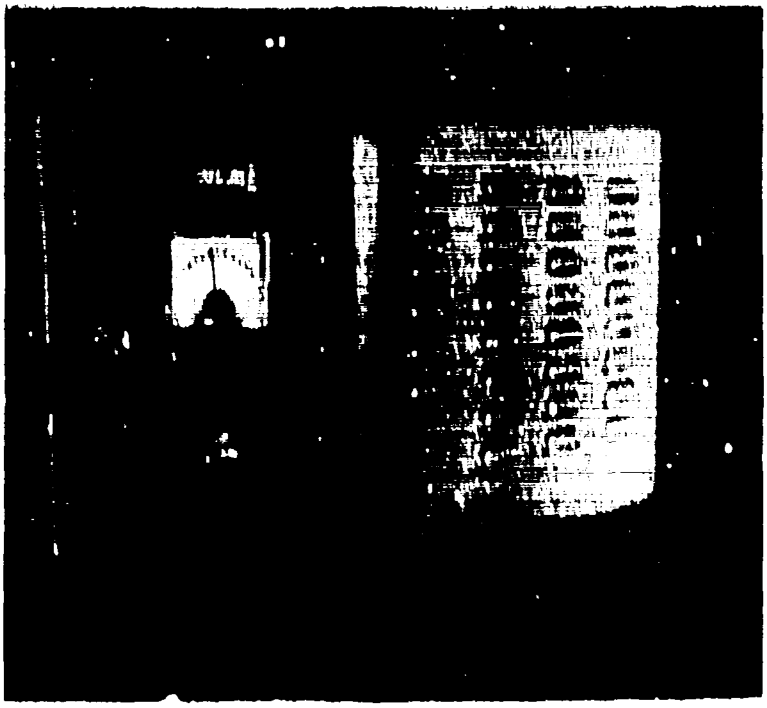

Figure 17 Magnatest Conductivity Meter, FM-100 Series, Used in Investigation of Non-Destructive-Test Methods (conductivity) (XP-77252)

V

ENVIRONMENTAL-TEST PROGRAM

The planned program objectives, test cycle, test and inspection procedures, and analysis of the test data are discussed in this section.

A. Planned Program Objectives

The objectives of the planned program may be defined as follows:

(1) To determine if welding and brazing have any degrading effect on the mechanical properties of specimens of the selected alloys after cyclic temperature exposure in the laboratory while such specimens are under constant load in a corrosive atmosphere.

(2) To determine if non-destructive testing methods have the ability to sense any corrosion which might occur on the alloys exposed to severe environmental conditions.

(3) To determine if there are effects of temperature at stress, number of cycles, and environment for the selected alloys after welding and brazing; and attempt to establish service lives for structural components fabricated from such alloys by methods which include welding and brazing.

(4) To evaluate welding and brazing as means of repair of specimens which have been weakened by corrosion resulting from severe environmental conditions, provided that the degradation has not been too severe.

B. Planned Test Cycle

The test cycle was programmed for four hours' duration, with the variable within that period being temperature and the constants being stress and corrosive atmosphere (simulated sea salt). A selected constant temperature was to be held for approximately three hours of the four-hour period; changing from room to test temperature was to consume the remaining hour. A four-hour cycle was selected because it approximated the flight cycle of transoceanic, Mach-3 aircraft.

The Cycle Variable: Temperature - The temperature ranges to be used in the environmental-test program were specified by the Contract. They were based upon typical operating-temperature regimes (cyclic) predicted for representative

Mach-3-aircraft welded and brazed hardware fabricated from the ten selected alloys. Welded and brazed alloys used in aircraft structures were to be tested in the range from 600F to 800F, those used for power-plant compressor components in the range from 800F to 1200F, and those used in power-plant hot-section locations in the range from 1600F to 2000F. The temperature ranges assigned to each alloy in the environmental-test program appear in Table X.

The Cycle Constant: Stress - Each specimen was to be run at a constant stress throughout its environmental test. The ranges of stress under which specimens were to be operated were specified by the Contract. The test stresses to be used were ninety-five per cent of the estimated minimum value of 0.2% yield strength or the stress to produce 0.5% to 1% creep during the test period, whichever was limiting. All of the iron-base alloys which were to be tested at 600F and 800F, with the exception of A 286 which was to be tested at high temperature (1200F), were yield-strength limited. All of the nickel-base alloys which were to be tested between 1600F and 2000F, and the A-286 specimens which were to be tested at high temperature, were creep limited. The 0.5%-creep data were used when the 1%-creep data were not available. The stress ranges are listed in Table X.

TABLE X

TEMPERATURES AND STRESSES FOR ENVIRONMENTAL TESTS

Material	Temperature (F)	Stress (psi)
AM 350	600 - 800	117,000 - 132,000
AM 355	600 - 800	117,000 - 130,000
PH15-7Mo	600 - 800	130,000 - 160,000
PH14-8Mo	600 - 800	148,000 - 160,000
Hastelloy X	1600 - 2000	1,000 - 3,500
René 41	1600 - 1800	3,000 - 17,000
Udimet 700	1600 - 1900	3,000 - 29,000
A 286	800 - 1200	30,000 - 83,000
Greek Ascoloy	600 - 800	83,000 - 95,000
TD Nickel	1600 - 2000	1,000 - 9,000

The Cycle Constant: Simulated Sea-Salt Atmosphere - The simulated sea salt was to result from the drying of certain chlorides and a sulphate in water solution, the chemical composition being 25.0 grams NaCl, 11.0 grams $MgCl_2 \cdot 6H_2O$, 4.0 grams Na_2SO_4, and 1.2 grams $CaCl_2$ per liter of distilled water. The sulphate was included because the Contractor's experience has been that Na_2SO_4, in combination with the chlorides, produces corrosion of a type frequently experienced under severe operating conditions. The presence of sulfur in this compound would enable the sulfidation type of corrosion to be investigated. The solution was to be applied by brush to the welded and brazed regions of the specimens, the extent of coverage to be approximately as shown in the sketch, Figure 18. Coatings were to be superimposed upon one another, each coating to be dried at approximately 250F. Final thickness of the salt deposit was to be approximately 0.002 inch.

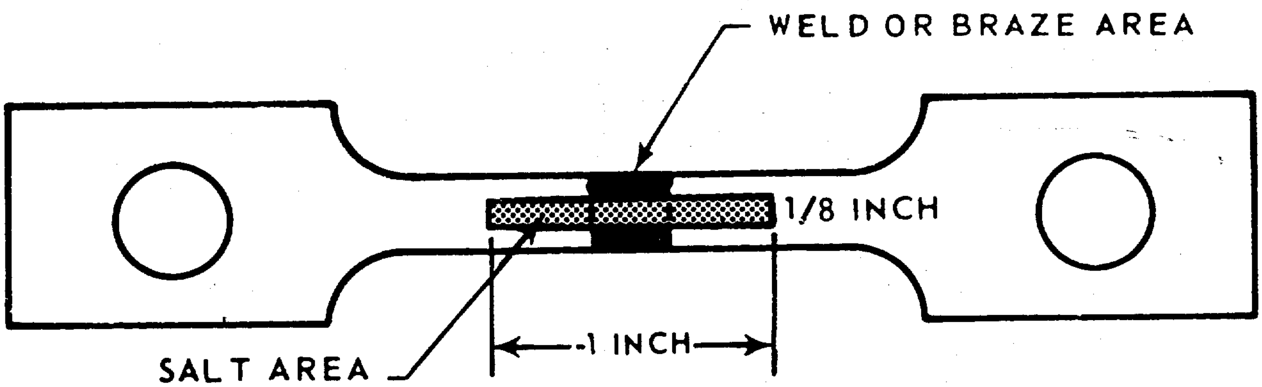

Figure 18 Approximate Location of Salt Patch on Specimen 67-258-2

C. Planned Test and Inspection Procedures

The test format which was scheduled, the planned duration of test conditions, the provisions for controls, the number of specimens tested, and the inspections made, are discussed in this subsection.

Test Format - Table XI shows the planned format for conducting the environmental testing of the ten selected alloys. Such a program would allow the estimation of all main effects of the environmental-test conditions and the determination of the interactions of those conditions.

Duration of Test Conditions - The fourteen test conditions defined in Table XI were of either sixty-three-cycles' or nineteen-cycles' duration, corresponding to two-hundred and fifty-two hours and seventy-six hours, respectively. The severity of the temperature-stress combination for the particular alloy and joining process to be tested depended upon the assignment of one or the other of the two limits. The durations selected were considered to be reasonably long periods of severe exposure for the hardware items which the alloys have application for in Mach-3 aircraft and their power plants.

TABLE XI

TEST FORMAT FOR ALLOY SPECIMENS

Test Condition[1]	Process	No. of Cycles	Temp.	Stress	Salt
1*	None	63	Upper (U)	Lower (L)(1)	Yes
2*	None	63	U	L (1)	No
3*	Braze	63	U	L (1)	No
4*	Weld	63	U	L	No
5*	Weld	63	L	U (2)	No
6*	Braze	63	L	U (2)	No
7	Weld	63	U	L	Yes
8	Weld	63	L	U (2)	Yes
9	Weld	19	U	L (3)	Yes
10	Weld	19	L	U (1)	Yes
11	Braze	63	U	L (1)	Yes
12	Braze	63	L	U (2)	Yes
13	Braze	19	U	L (3)	Yes
14	Braze	19	L	U	Yes

Notes: (1) Controls are marked by asterisks

(2) Intermediate value used to TD Nickel

(3) Intermediate value used for Hastelloy X, René 41, Udimet 700, and TD Nickel

(4) Intermediate value used for Hastelloy X, A 286, René 41, Udimet 700, and TD Nickel

Controls - Four different classes of controls for each material were to be exposed to their respective test conditions. These controls were to be utilized for evaluating the extent of detriment, if any, to mechanical properties of the alloys which was attributable to the joining processes. The four classes of controls are listed below.

	Salt	Process
(1)	Yes	None
(2)	No	None
(3)	No	Weld
(4)	No	Braze

For evaluation of any degradation of the mechanical properties of repaired specimens, control specimens of the same materials were to be tensile tested under ambient conditions, along with specimens which had been repaired after being exposed to the environmental-test condition which resulted in the original degradation of mechanical properties.

Number of Specimens - The Contract specified that the maximum number of specimens evaluated would be four hundred: a maximum of fifteen welded and control specimens and a maximum of fifteen brazed and control specimens, of each of the ten alloys; a maximum of eighty non-destructive-test specimens; and a maximum of twenty repair specimens.

Inspection - Macroscopic, radiographic, fluorescent-penetrant, ultrasonic, electrical-conductivity, and beta-ray-backscatter inspections, all non-destructive-test methods, were to be performed on specimens immediately prior to their exposure to their cyclic-test program. These methods of inspection were also to be employed after ten (40 hours) and nineteen cycles had been logged on specimens limited to nineteen-cycle testing, and after ten, forty (160 hours), and sixty-three cycles had been logged on those programmed for sixty-three-cycle testing. For the ten-cycle and forty-cycle inspections, salt-coated specimens were to be cleaned before examination and thereafter have their salt coatings restored. Specimens failing to complete their tests were to be subjected to metallographic study. Such testing was also to be employed on sound specimens after non-destructive-test data were obtained and after mechanical testing was performed. Fractured specimens were to be given macroscopic examinations in order to detect any discoloration on fracture surfaces. Such discoloration would be indicative of prior cracks resulting from environmental testing. The amount of shear was to be determined, in order to ascertain if observed cracks propagated primarily in a ductile or in a brittle fashion; also, the point of transition was to be ascertained, if both ductile and brittle types were found.

D. Data Analysis

It was necessary to analyze the test data in such a way that the effects of each variable in the program could be isolated from the effects of the other variables. It was decided to tabulate the effects as positive or negative percentage changes in the magnitude of each property, a positive change indicating an increase and a negative change a decrease. Blanks in the tabulation were to indicate that the available data were not significant, and dash marks that data from which the effect could be calculated were not available. Changes of less than five per cent in strength were to be considered insignificant because such small changes would fall within the expected range of normal data variation. The accuracy of measurement was less for elongation than for strength and the elongations which were measured were, in general, low. Therefore, the level of significance for percentage changes in elongation was selected to be thirty per cent. For the reasons which have been indicated, the effects of the environmental test variables would be determined primarily from the results obtained for ultimate and yield strengths.

The test conditions for which data were obtained are presented in Table XII. The data from duplicate test points were averaged, those from individual points were used as recorded. ~~The measured values of ultimate and yield~~ strengths, in thousands of pounds per square inch, were rounded to the nearest whole numbers. These data were then tabulated in the arrangement shown in Table XIII, wherein the values for x and y are to be taken from the data corresponding to the conditions listed by line number in Table XII. The percentage changes in properties were then computed as follows:

$$\text{Per cent change in strength} = \frac{x-y}{x}\,100$$

$$\text{Per cent change in elongation} = \frac{x-y}{\text{the larger of } x \text{ and } y}\,100$$

TABLE XII

ALLOY-SPECIMEN TEST CONDITIONS FOR USE IN DATA ANALYSIS

Line No.	Joint	Salt	Temperature	Cycles
1	Weld	No	Room	None
2	Weld	No	Low	High
3	Weld	No	High	High
4	None	No	High	High
5	None	Yes	High	High
6	Weld	Yes	High	High
7	Weld	Yes	High	Low
8	Weld	Yes	Low	High
9	Weld	Yes	Low	Low
10	Braze	No	Room	None
11	Braze	No	Low	High
12	Braze	No	High	High
13	None	No	High	High
14	None	Yes	High	High
15	Braze	Yes	High	High
16	Braze	Yes	High	Low
17	Braze	Yes	Low	High
18	Braze	Yes	Low	Low

TABLE XIII

DEFINITION OF CONDITION SETS FOR USE IN DATA ANALYSIS

Condition Set Number	Line No. in Table XII For Welded Specimens		Line No. in Table XII For Brazed Specimens	
	For x data	For y data	For x data	For y data
1	3	6	12	15
2	2	5	11	17
3	6	8	15	17
4	7	9	16	18
5	6	7	15	16
6	8	9	17	18
7	4	8	13	12
8	5	6	14	15

VI

ENVIRONMENTAL-TEST RESULTS

The program of testing which was carried out followed closely the planned program discussed in Section V.

The test results relating to each alloy are discussed in subsection A below. The evaluation of non-destructive-testing methods for measuring degradation of mechanical properties of the alloys due to corrosion is reported in subsection B. The final subsection, C, summarizes the more significant results of the program.

Three types of salt corrosion were considered in the evaluation of specimens:

Type (1) Evidenced by localized discoloration on the fracture surface, indicating the existence of a crack during exposure of the specimen to elevated temperatures.

Type (2) Evidenced by post-exposure, room-temperature, tensile-property degradation.

Type (3) Evidenced by unusual cracking during post-exposure, room-temperature, tensile testing.

A. Specific Findings

Table XIV categorizes the test results into whether or not salt corrosion was encountered (1) at inspection following post-exposure tensile testing of specimens which survived for the programmed number of cycles, and (2) at examination of specimens following failure during cyclic testing. This information is given for both brazed and welded specimens of the two classes of alloys, iron-based and nickel-based. Table XV presents the results of the analysis of data for the entire program. The columns numbered one through eight in this Table contain the percentage-change values for the eight condition sets listed in the first column of Table XIII and defined by reference to the lines in Table XII. A review of the specific findings for each alloy follows.

AM 350 (Welded) - Table XVI presents the environmental-test history for welded and brazed AM 350 specimens. In this table, as in those for the other alloys in the program, the exposure conditions and the post-exposure, room-temperature, tensile properties are listed for each specimen subjected to test. Also noted are the number of test cycles completed, location of failure on tensile test, and whether or not Type-(1) and/or Type-(3) salt corrosion were evident.

TABLE XIV

SUMMARY OF RESULTS OBTAINED FROM ENVIRONMENTAL-TEST PROGRAM

Specimen Material	Non-Brazed Control Specimens		Brazed Specimens				Non-Welded Control Specimens		Welded Specimens			
	Cyclic Environmental Failure No Corrosion	Post-Exposure Tensile Failure No Corrosion	Cyclic Environmental Failure No Corr.	Cyclic Environmental Failure Corr.	Post-Exposure Tensile Failure No Corr.	Post-Exposure Tensile Failure Corr.	Cylic Environmental Failure No Corr.	Post-Exposure Tensile Failure No. Corr.	Cyclic Environmental Failure No. Corr.	Cyclic Environmental Failure Corr.	Post-Exposure Tensile Failure No. Corr.	Post-Exposure Tensile Failure Corr.
Iron Base												
AM 350		X				X		X				X
AM 355		X			X			X			X	
PH15-7Mo		X				X*		X			X	
PH14-8Mo	X			X				X			X	
Greek Ascoloy		X			X			X			X	
A 286		X				X		X				X
Nickel Base												
Hastelloy X		X				X		X			X	
Rene 41		X				X	X					X
Udimet 700	X					X	X					X**
TD Nickel	X			X			X		X			

*Corrosion not necessarily attributable to salt.

**Sulfidation

TABLE XV

EFFECTS OF ENVIRONMENTAL-TEST VARIABLES ON MECHANICAL PROPERTIES OF ALLOY SPECIMENS

(Numbers indicate percentage changes in mechanical properties)

Material Condition [1]			Salt at 63 Cycles with Joint in Material		Temperature with Salt and Joint		Cycles with Salt and Joint		Joint at 63 Cycles and High Temp	
			Col. 1 High Temp	Col. 2 Low Temp	Col. 3 63 Cycles	Col. 4 19 Cycles	Col. 5 High Temp	Col. 6 Low Temp	Col. 7 No Salt	Col. 8 Salt
A. AM 350	Welded	UTS			+5		+5			
		YS			+6		+6		-30	
		EL	+46				+30		--	
	Brazed	UTS							--	
		YS			+5		+5		--	
		EL			-40	-62	+48			
B. AM 355	Welded	UTS			+12	+9	+6			-5
		YS			+12	+9	+6		-35	-30
		EL			-70	-30				
	Brazed	UTS			+12	+8				
		YS			+12	+10				
		EL								
C. PH15-7Mo	Welded	UTS			+9	+7			-6	-5
		YS	--		--	+8	--		-7	--
		EL		+70	-72		-50	+50	-70	-70
	Brazed	UTS	+12 (2)		+8	--	--		-18	-11
		YS	--	--	--	--	--		--	--
		EL	+58 (2)	-10	-79	--	--		-85	-70
D. PH14-8Mo	Welded	UTS			+9	+5	+5			--
		YS			+12	+5	+5			--
		EL							--	--
	Brazed	UTS	--		--	--	--	+5	--	--
		YS	--		--	--	--	+6	--	--
		EL	--		--	--	--			--
E. Hastelloy X	Welded	UTS* (3)	--		--	--	--	-5	--	--
		YS*	--		--	--	--		--	--
		EL*	--		--	--	--		--	--
	Brazed	UTS	-25	-19	-35	--	--	-7	+5	-14
		YS*			-18	--	--	-12		
		EL*	-55	-45	+43	--	--			
F. René 41	Welded	UTS	-28	-10	-56	-22	-40	-11	--	--
		YS	-12	-7	-58	-47	-17	-9	--	--
		EL	-66		+39	+71	-61		--	--
	Brazed	UTS	-48	--	--		-13	--		-8
		YS	--	--	--	--	--	—		--
		EL	--	--	--	--	--	--		--
G. Udimet 700	Welded	UTS*	--		--	--	--	-11	--	--
		YS*	--		--	--	--	-9	--	--
		EL*	--		--	--	--		--	--
	Brazed	UTS*	--	-23	--	-12	--	-18	--	--
		YS*	--	-5	--	-7	--	-11	--	--
		EL*	--	-60	--		--	-60	--	--
H. A286	Welded	UTS	-6		+7	+7			-5	-9
		YS			+8	+6	+5		-65	--
		EL								
	Brazed	UTS	-12		-7		-10			-7
		YS	-11			+6	-11	-6		-9
		EL			-33					
I. Greek Ascoloy	Welded	UTS								
		YS		-7	+5	+6	-5			
		EL								
	Brazed	UTS							--	--
		YS			-5				--	--
		EL							--	--
J. TD Nickel	Welded	UTS*	--	--	--	--	--	--	--	--
		YS*	--	--	--	--	--	--	--	--
		EL*	--	--	--	--	--	--	--	--
	Brazed	UTS*	--		--	--	--	-21	--	--
		YS*	--		--	--	--	+53	--	--
		EL*	--	+54	--	--	--			

Notes: (1) Yield strengths are 0.2%
(2) Corrosion effect not necessarily attributable to salt
(3) Asterisks indicate high-temperature test conditions too severe

TABLE XVI

ENVIRONMENTAL-TEST HISTORY: AM-350 ALLOY SPECIMENS

		[illegible]					[illegible]						[illegible]
Specimen No.	Joint Type	Salt	Temp (F)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Failure Loc.(1)	Salt Corrosion(2)	[illegible]
A-1	Weld	Yes	800	117	63	63	[illegible]	[illegible]	4	[illegible]	1	Yes	[illegible]
A-2	Weld	Yes	[illegible]		63	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	Yes	[illegible]
A-3	Weld	Yes	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1	No	[illegible]
A-4	Weld	Yes	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1	No	[illegible]
[illegible]	Weld	No	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1	-	[illegible]
A-10	Weld	No	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1	-	[illegible]
A-11	Weld	No	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1	-	[illegible]
A-12	Weld	No	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	1	-	[illegible]
[illegible]	Weld	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]		No	[illegible]
A-14	Weld	Yes	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1	No	[illegible]
A-15	Weld	Yes	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1	No	[illegible]
A-17	Weld	Yes	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1	No	[illegible]
A-18	Weld	-	-	-	-	-	[illegible]	[illegible]	[illegible]	[illegible]	1	-	[illegible]
[illegible]	None	No	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-	-	[illegible]
[illegible]	None	Yes	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1	No	[illegible]
[illegible]	Braze	Yes	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible](3)	Yes	[illegible]
[illegible]	Braze	Yes	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	No	[illegible]
[illegible]	Braze	Yes	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	No	[illegible]
[illegible]	Braze	Yes	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	No	[illegible]
[illegible]	Braze	No	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1	-	[illegible]
[illegible]	Braze	No	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1(4)	-	[illegible]
[illegible]	Braze	No	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-	[illegible]
[illegible]	Braze	No	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-	[illegible]
[illegible]	Braze	Yes	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	No	[illegible]
[illegible]	Braze	Yes	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	No	[illegible]
[illegible]	Braze	Yes	[illegible]	[illegible]	[illegible]	[illegible]	-	-	-	100	[illegible]	No	[illegible]
[illegible]	Braze	Yes	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible](3)	Yes	[illegible]
[illegible]	Braze	-	-	-	-	-	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-	[illegible]
[illegible]	None	No	[illegible]	[illegible]	[illegible]	[illegible]	-	-	-	100	-	-	[illegible]
[illegible]	None	Yes	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	No	[illegible]

Notes. (1) [illegible]
1. Through joint
2. Away from joint but through salt
3. Away from salt
4. Away from joint (no salt on specimen)
5. Through salt (no joint)

(2) Salt corrosion of Types 1 and/or 2, as identified in text
(3) Fracture originated at Type-1 corrosion area
(4) Fracture originated at [illegible] in braze

As Tables XIV and XVI indicate, salt-corrosion cracking was observed in welded AM 350. In the case of this alloy, the depths of the discrepancies measured did not exceed 0.005 inch. Only one specimen, A-1, evidenced Type-(1) corrosion, but the tensile failure did not originate at the crack and the strength and ductility were not compromised. Failure occurred through the weld (Figure 19). Exposure conditions under which the cracking occurred were 800F and 117 ksi for 63 cycles. The discoloration on the fracture surface can be seen in Figure 20. The specimen was also found to have several irregular, intergranular cracks adjacent and parallel to the tensile-test-fracture surface, as Figure 21 indicates (arrows). These cracks were confined to the salt-patch region (Type-(3) corrosion). A photomicrograph through the cracked area is shown in Figure 22.

Figure 19 Welded Specimen A-1 After Tensile Test. Specimen Macroetched to Show Location of Rupture. (Environmental-test conditions: 800F, 117 ksi, salt; duration: 63 cycles) (XP-2172-2)
Etchant: Villela's Reagent Mag: 20X

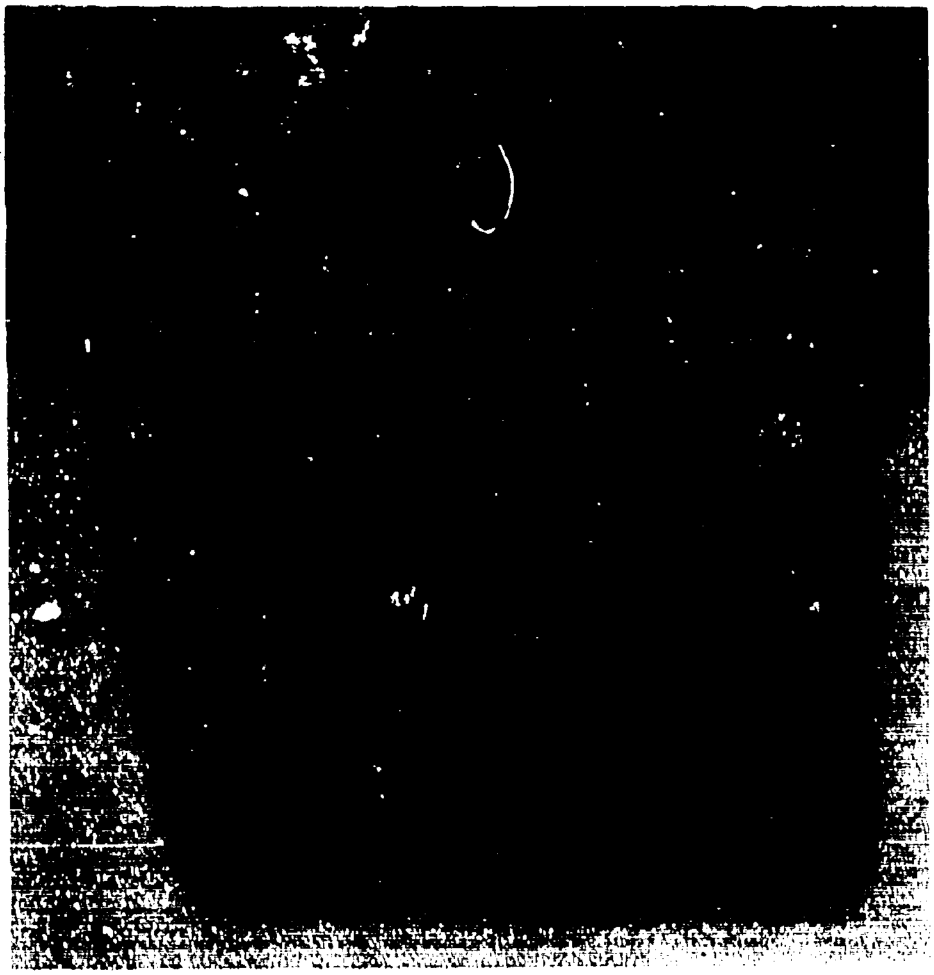

Figure 20 Welded Specimen A-1 After Tensile Test. Arrow Points to Crack Indication. (Environmental test conditions: 800F, 117 ksi, salt; duration: 63 cycles) (H-64457)
Mag: 24X

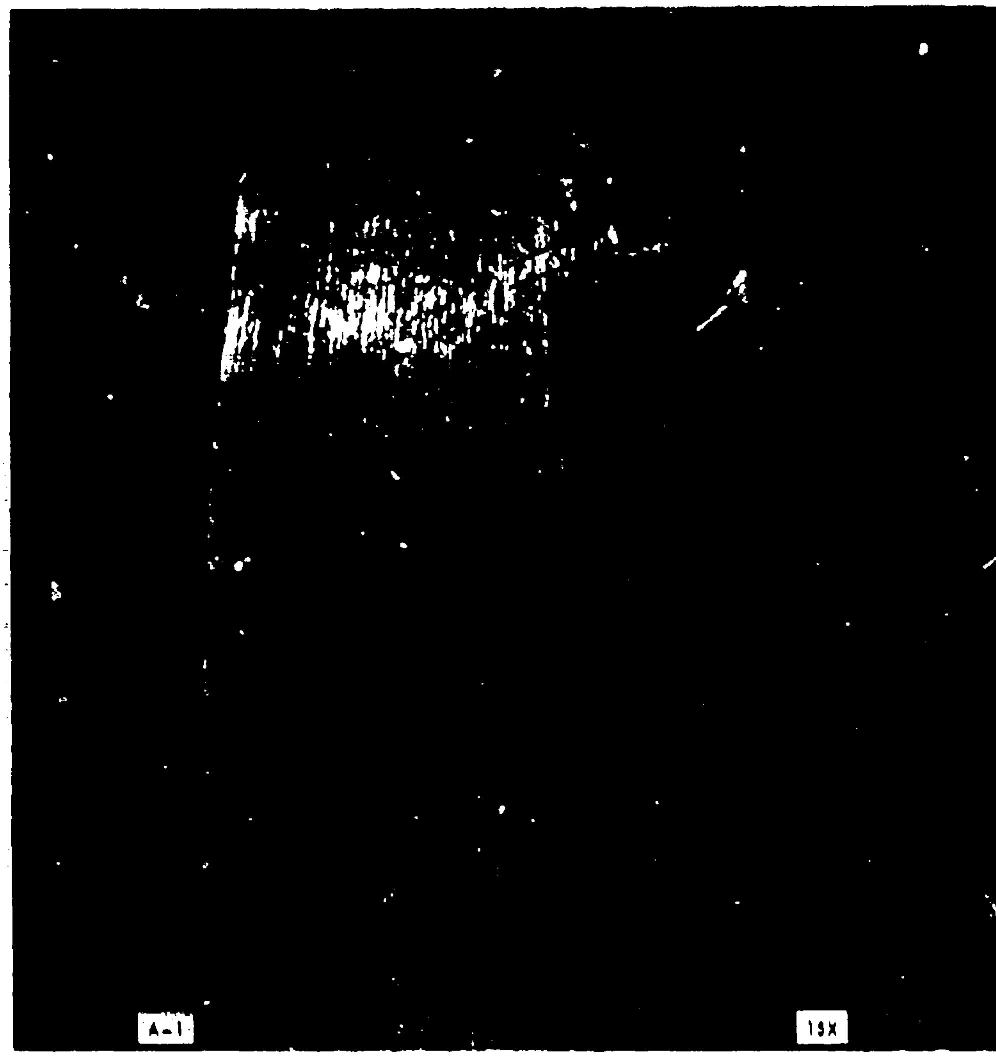

Figure 21 Welded Specimen A-1 After Tensile Test. Cracks (Arrows) are Confined to Salt Patch. (Environmental-test conditions: 800°F, 117 ksi, salt; duration: 63 cycles) (H-64455)
Mag: 15X

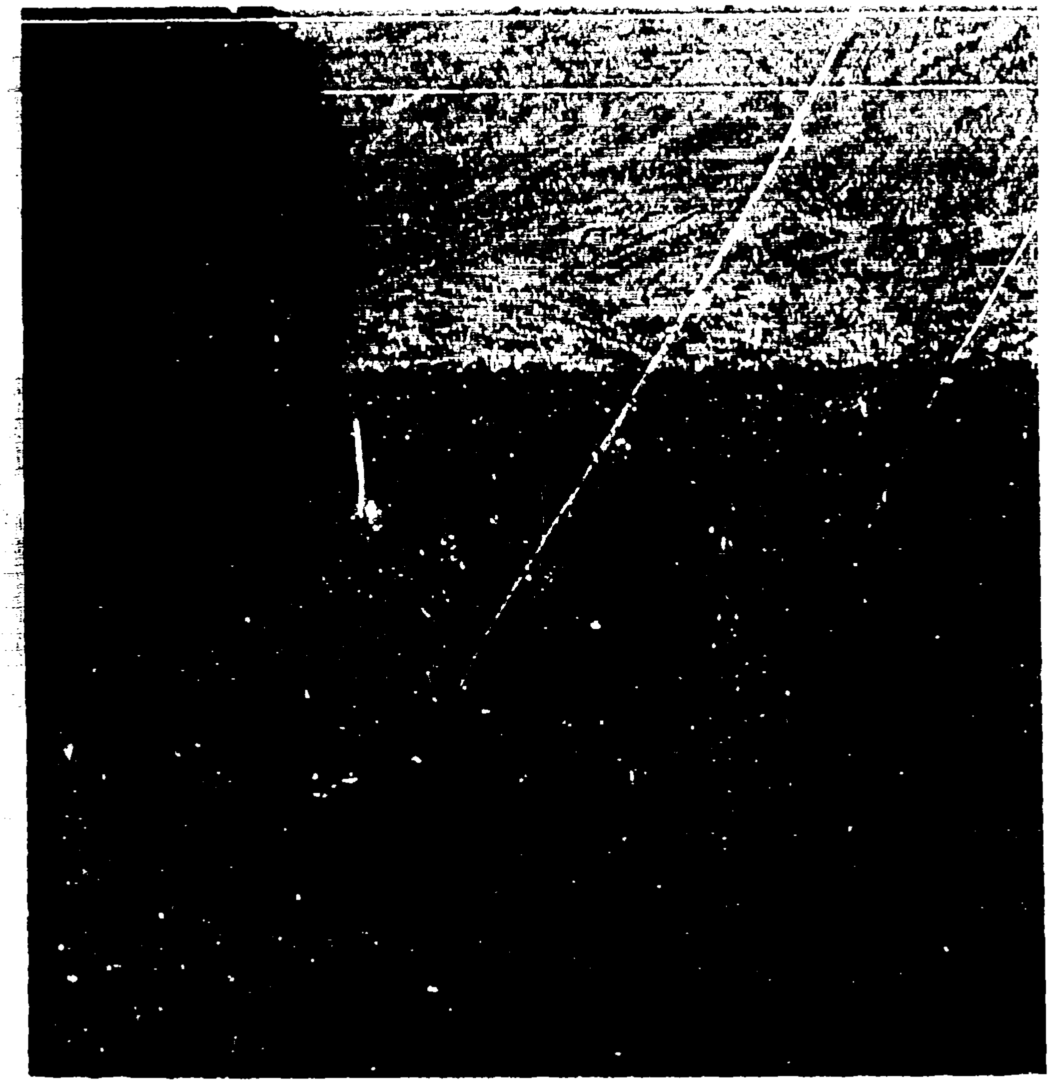

Figure 22 Welded Specimen A-1 After Tensile Test. Photomicrograph of Section Through Specimen Adjacent to Fracture Surface. (Environmental-test conditions: 800F, 117 ksi, salt; duration: 63 cycles)
(EP-2748-2)

Etchant: Villela's Reagent Mag: 200X

A second specimen in the welded group (A-3) evidenced Type-(3) corrosion after exposure. This specimen had completed 63 cycles under 600-F and 132-ksi conditions. The cracks were confined to the salt patch (see Figure 23).

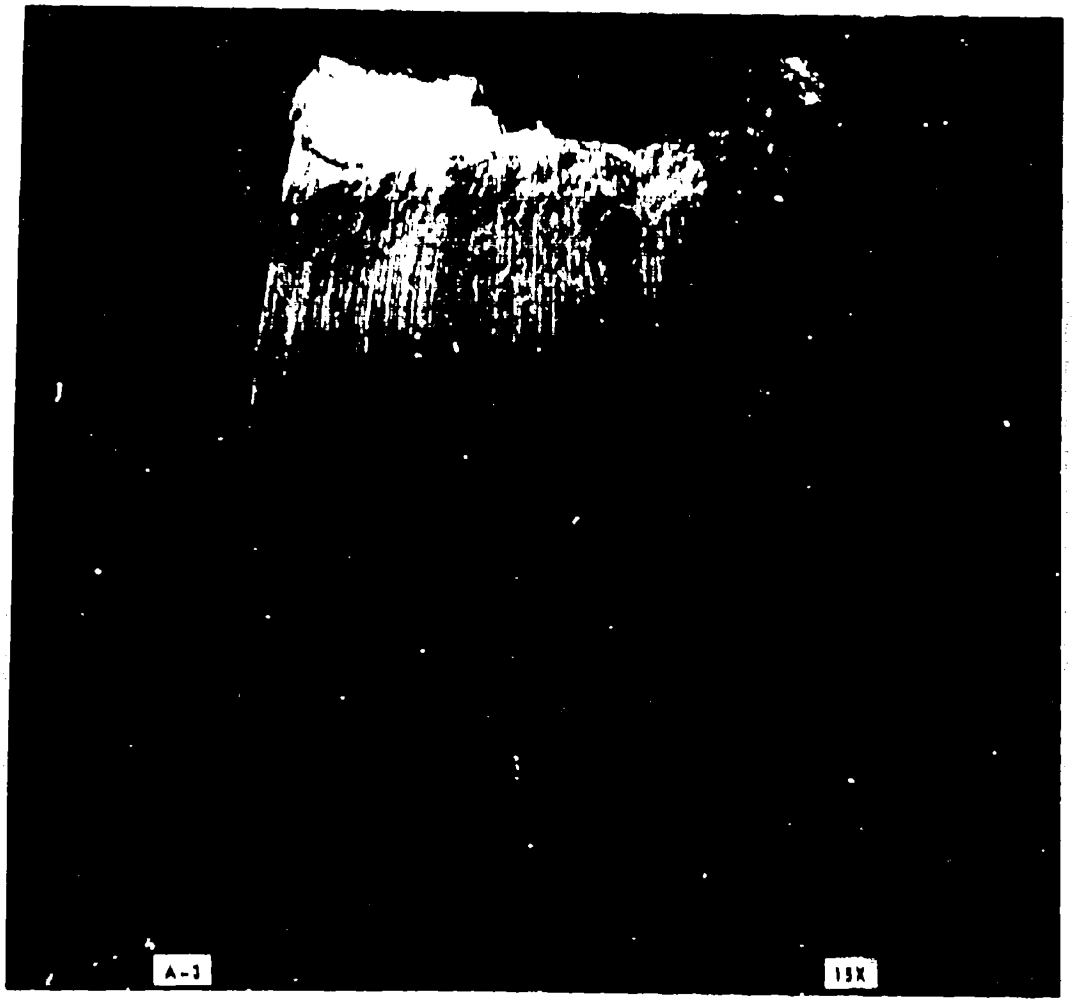

Figure 23 Welded Specimen A-3 After Tensile Test. Cracks (Arrows) are Confined to Salt Patch. (Environmental-test conditions: 600°F, 132 ksi, salt; duration: 63 cycles) (H-64456) Mag: 15X

AM 350 (Brazed) -- Two instances of Type-(1) corrosion were encountered when brazed specimens were examined after exposure and tensile test. Reference to Table XVI indicates that both specimens (A-21 and A-34) had been cycled at 800 F and that for one (A-34) the corrosion had occurred within 19 cycles. The elongations of the two specimens were found to have been significantly reduced by the environmental-test exposure, in comparison with the elongation of the one welded specimen with Type-(1) corrosion. However, there was no indication of any degradation of ultimate-tensile and 0.2% yield strengths. Figures 24 and 25 show the tensile-failure locations of these specimens with relation to the brazed area and also the degree of braze deterioration. The failures occurred outside of the brazed areas but within the salt patch. Figures 26 and 27 reveal the corrosion indications on the fracture surfaces of specimens A-21 and A-34. Both fractures originated in the discolored regions. Also, both specimens had several irregular, intergranular cracks adjacent and parallel to the fracture surface and within the salt-stained regions on their lateral surfaces (Type-(3) corrosion). Cracks of this character can be seen in Figures 28, 29, and 30.

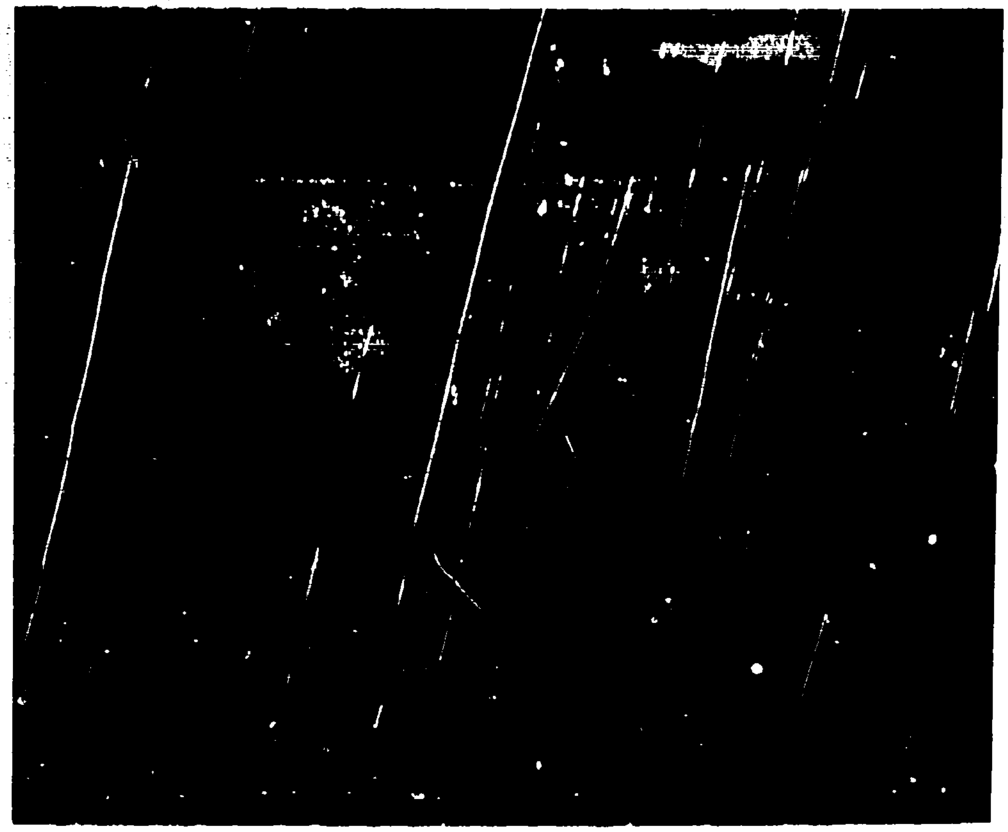

Figure 24 Brazed Specimen A-21 After Tensile Test, Showing Location of Rupture. (Environmental-test conditions: 800F, 117 ksi, salt; duration: 63 cycles) (H-03991)
Mag: 15X

Figure 25 Brazed Specimen A-34 After Tensile Test, Showing Location of Rupture. (Environmental-test conditions: 900F, 117 ksi, salt; duration: 19 cycles) (EP-2172-12) Mag: 20X

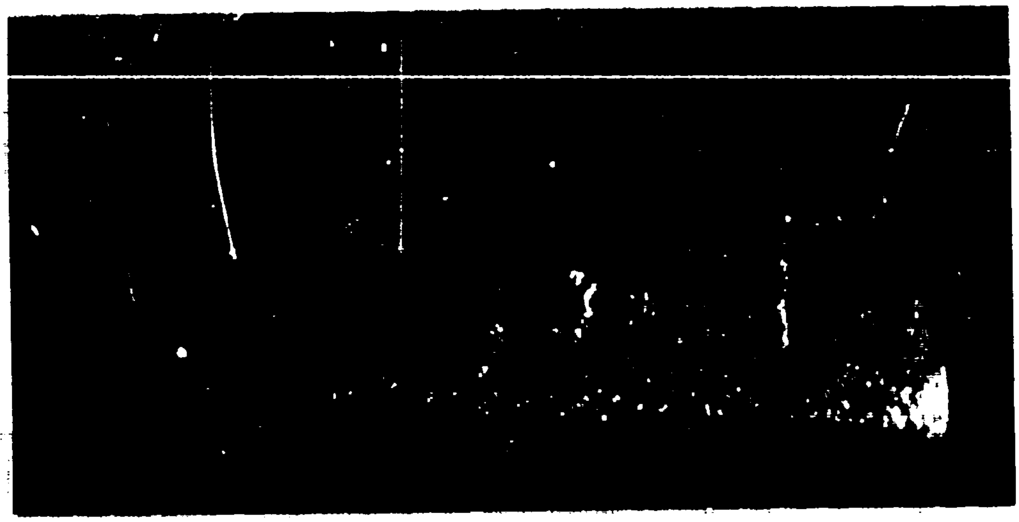

Figure 26 Brazed Specimen A-21 After Tensile Test. Fracture Surface Shows Type-(1)-Salt-Corrosion Indication (arrow). (Environmental-test conditions: 800F, 117 ksi, salt; duration: 63 cycles)
(H-64066)
Mag: 24X

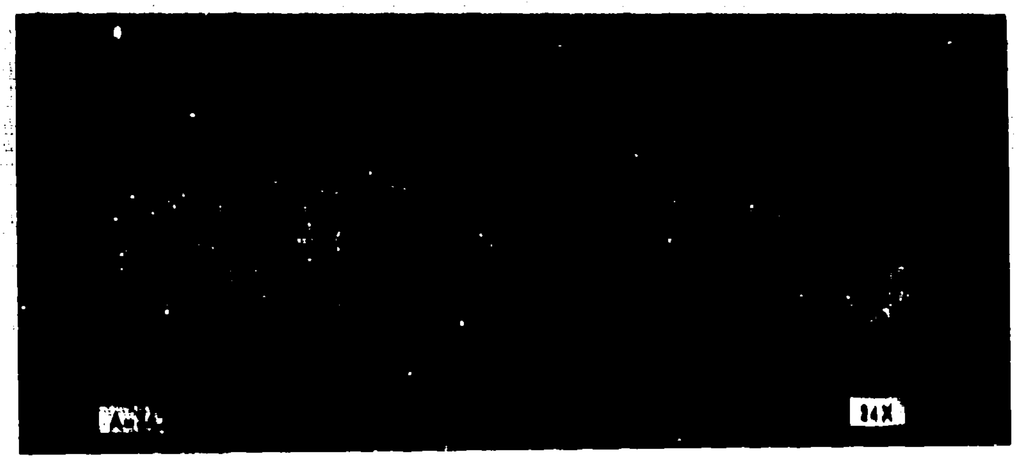

Figure 27 Brazed Specimen A-34 After Tensile Test Showing Corrosion Indication (Arrow). (Environmental-test conditions: 800°F, 117 ksi, salt; duration: 19 cycles)
(H-64065)
Mag: 24X

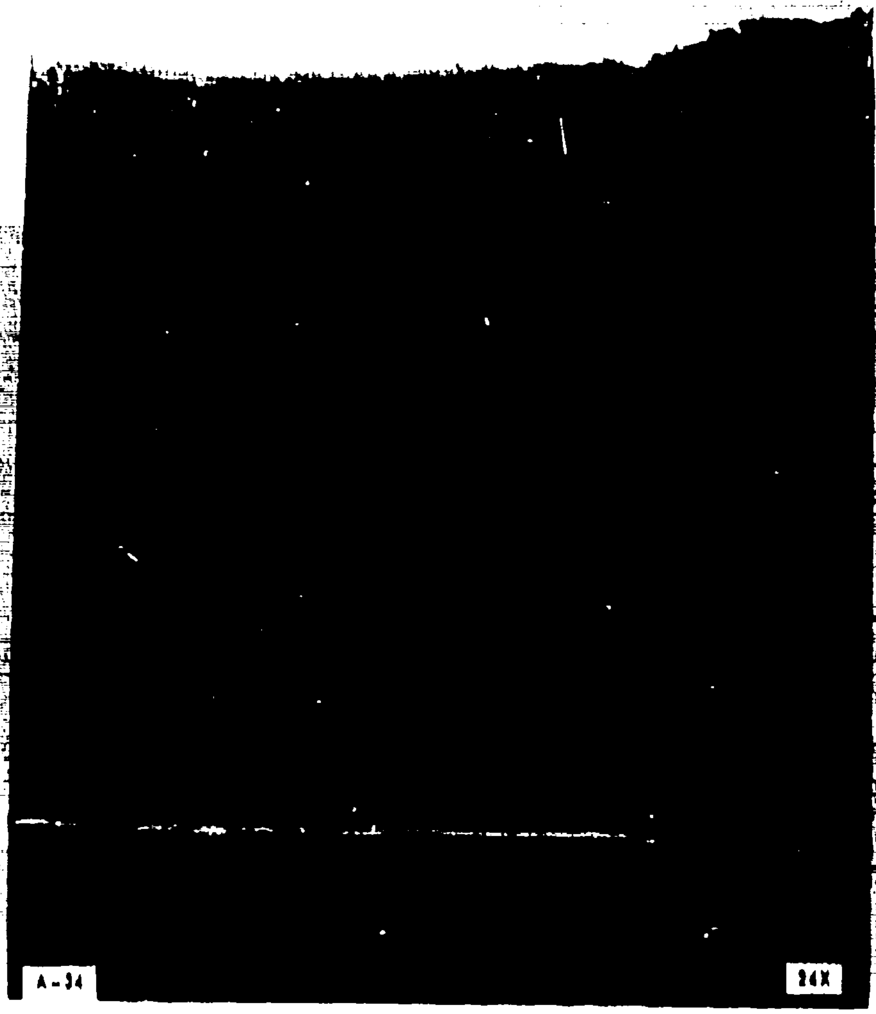

Figure 28 Brazed Specimen A-34 After Tensile Test. Lateral Surface Adjacent to Fracture Surface. (Environmental-test conditions: 800F, 117 ksi, salt; duration: 19 cycles)

Mag: 24X

Figure 29 Brazed Specimen A-34 After Tensile Test. Photomicrograph of Section Through Specimen Adjacent to Fracture Surface. (Environmental-test conditions: 800F, 117 ksi, salt; duration: 19 cycles)
Etchant: Villela's Reagent Mag: 375X

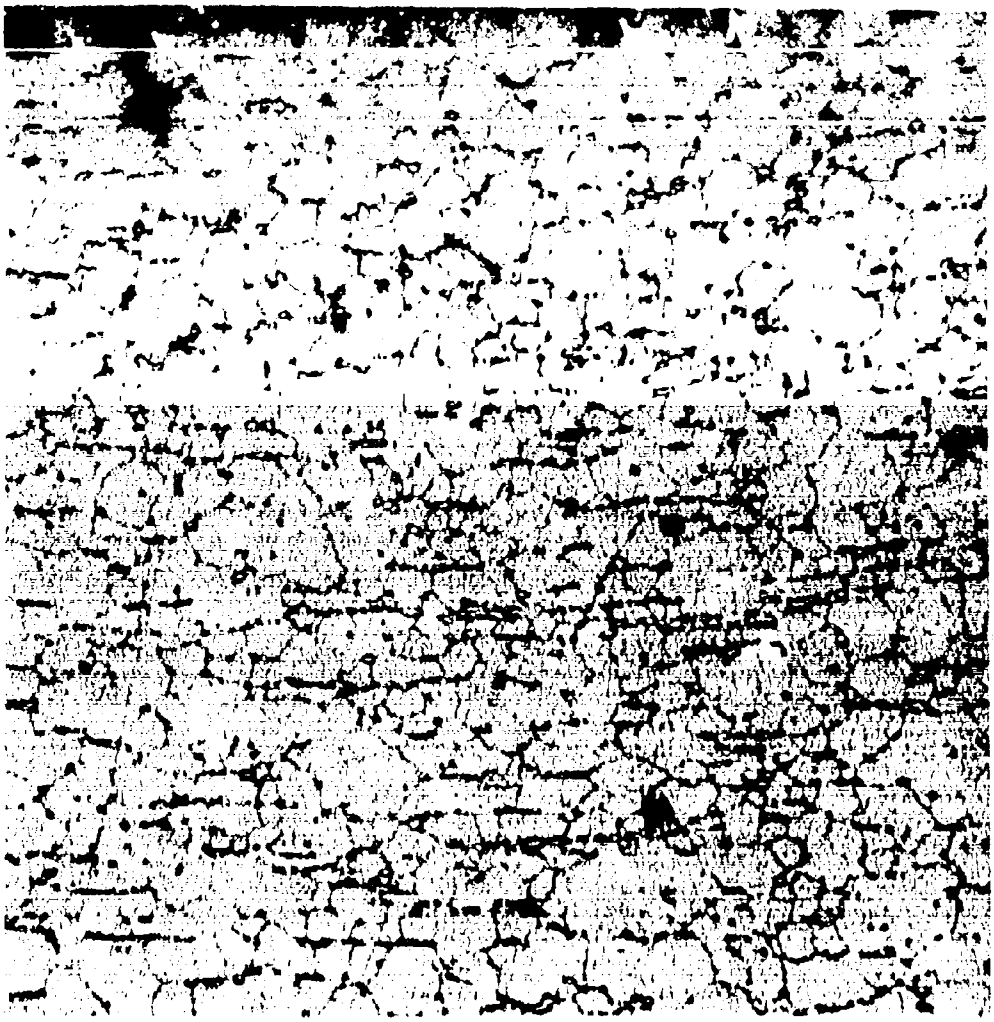

Figure 30 Brazed Specimen A-21 After Tensile Test. Photomicrograph of Section Through Specimen Adjacent to Fracture Surface Showing Cracks (Arrows) in Salted Region. (Environmental-test conditions: 800°F, 117 ksi, salt; duration: 63 cycles) (EP-2187-7)

Etchant: Villela's Reagent Mag: 500X

As indicated in Table XVI, two specimens failed during the first cycle of environmental testing. One of these specimens was brazed and salted (A-26); the second (A-30) was a non-brazed, unsalted control. Exposure conditions were 800F and 117 ksi. The mechanism of failure in both instances was not readily apparent. However, it was not salt corrosion based on the definitions used in this report.

Specimen A-30, a control which was brazed but unsalted, exhibited low ductility on tensile test after exposure for 63 cycles under 800-F and 117-ksi conditions. Examination of its fracture surfaces after tensile test disclosed that failure originated in a region where braze material had apparently penetrated parent metal. This can be seen by referring to Figures 31 and 32.

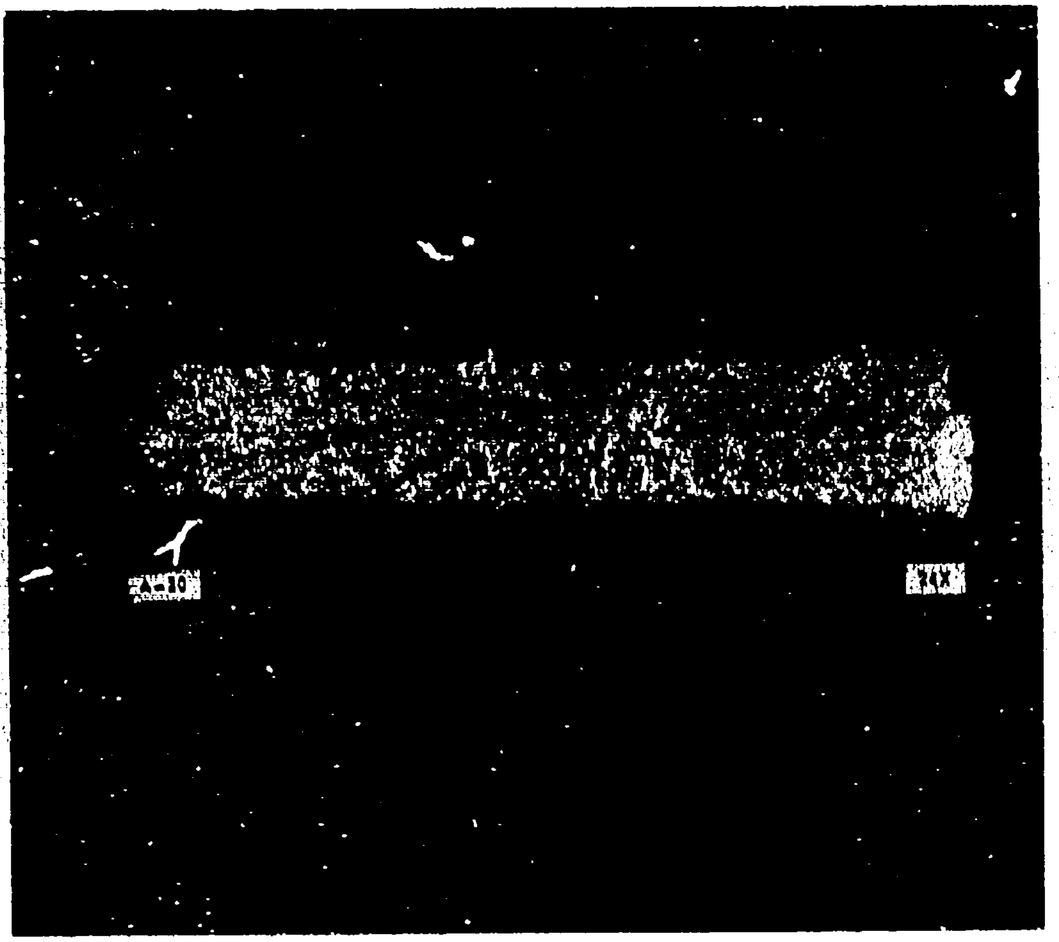

Figure 31 Brazed Specimen A-30 After Tensile Test Showing Failure Origin (Arrow) on Fracture Surface. (Environmental-test conditions: 800°F, 117 ksi, no salt; duration: 63 cycles (H-64067)
Mag: 24X

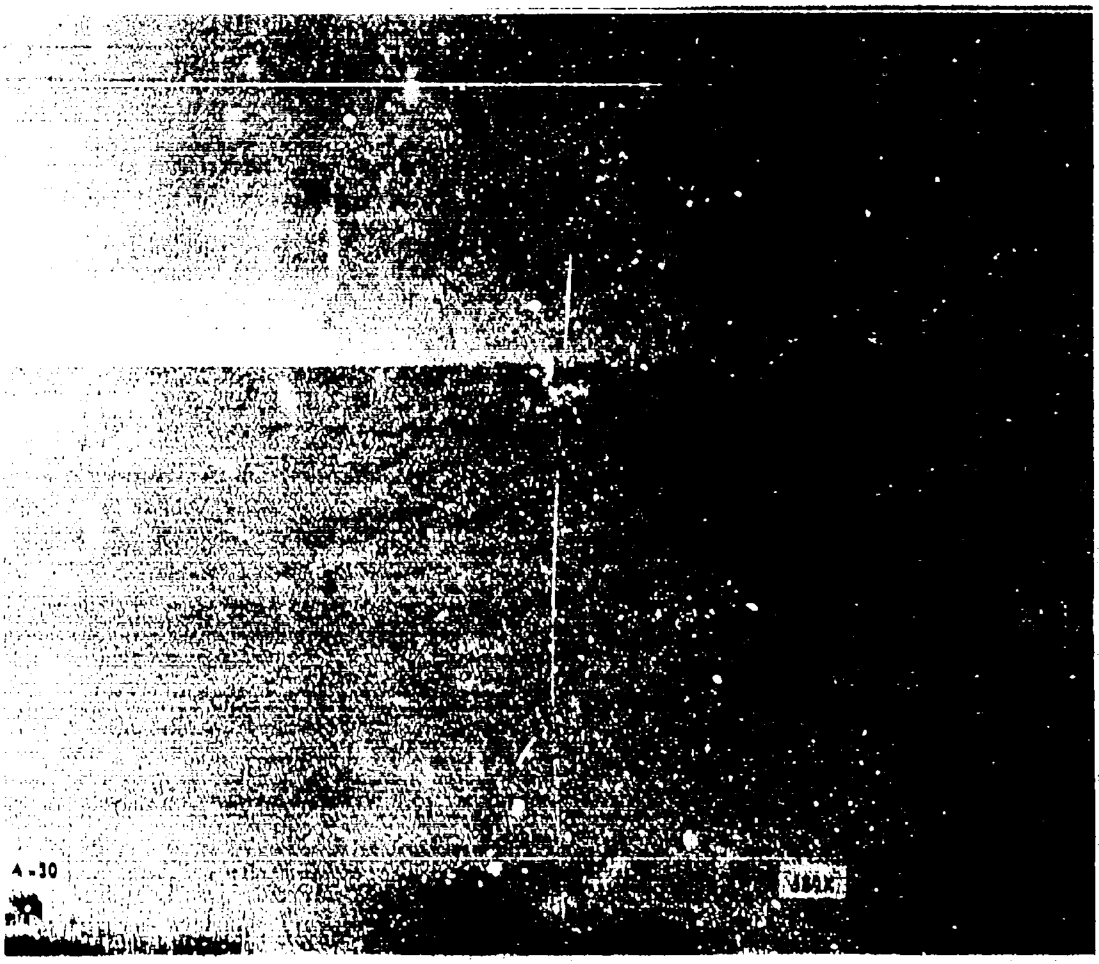

Figure 32 Brazed Specimen A-30 After Tensile Test. Photomicrograph of Section Through Fracture. (Environmental-test conditions: 800F, 117 ksi, no salt; duration: 63 cycles) (EM-2022-3)

Etchant: Villela's Reagent Mag: 350X

AM 350 (General) - The effects of the environmental exposure of AM-350 specimens were apparent only after post-exposure, room-temperature, tensile tests had been conducted and the tensile-fracture surfaces had been examined microscopically. In the four instances in which evidence of Type-(1) and/or Type-(3) corrosion were detected, metallographic examinations of the cross-sections failed to reveal the presence of any reaction products in the salted regions.

It should be noted that, as the data in Tables XVI and XV indicate, no effect of corrosion on strength was found and both welded and brazed specimens of AM-350 alloy demonstrated increased strengths after being exposed to the high cycles and high temperature. This is attributed to additional aging and is substantiated by the hardness values shown in Table XVI. Joining had no effect on strength after exposure.

AM 355 (Welded and Brazed) - Table XVII presents the environmental-test history for welded and brazed AM-355 specimens. Room-temperature tensile testing of the specimens, following environmental-test exposure, revealed no degradation due to the exposure and all showed an increase in tensile strength. Specimens exposed to the higher temperature (800F) exhibited greater strength increases relative to their lower-temperature counterparts. Hardness values increased correspondingly. The increases were attributed to the additional aging which resulted from exposure at the test temperatures.

TABLE XVII

ENVIRONMENTAL-TEST HISTORY: AM-355 ALLOY SPECIMENS

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Weld	Yes	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Weld	Yes	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Weld	Yes	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Weld	Yes	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Weld	No	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Weld	No	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Weld	No	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Weld	No	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Weld	Yes	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Weld	Yes	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Weld	Yes	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Weld	Yes	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Weld	-	-	-	-	-	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Braze	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Braze	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Braze	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Braze	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Braze	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Braze	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Braze	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Braze	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Braze	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Braze	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Braze	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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Notes: (1) [illegible]

Upon examination of the fractured specimens after tensile testing, no evidence of salt-corrosion cracking was observed. Furthermore, microscopic examination of a sampling of the specimens failed to reveal any evidence of corrosion cracks or of microstructural changes in the salted regions.

The data in Tables XVII and XV indicate that there was no effect of salt on strength. High temperature at high and low cycles and high cycles at high temperature increased strength. Joining had no effect on strength after the joined material was exposed.

Visual examination of the brazed specimens, conducted subsequent to environmental exposure, revealed some deterioration. As shown in Figures 33 and 34, the braze tended to separate from the base metal around its periphery. This effect was noted in salted and unsalted specimens at both exposure temperatures.

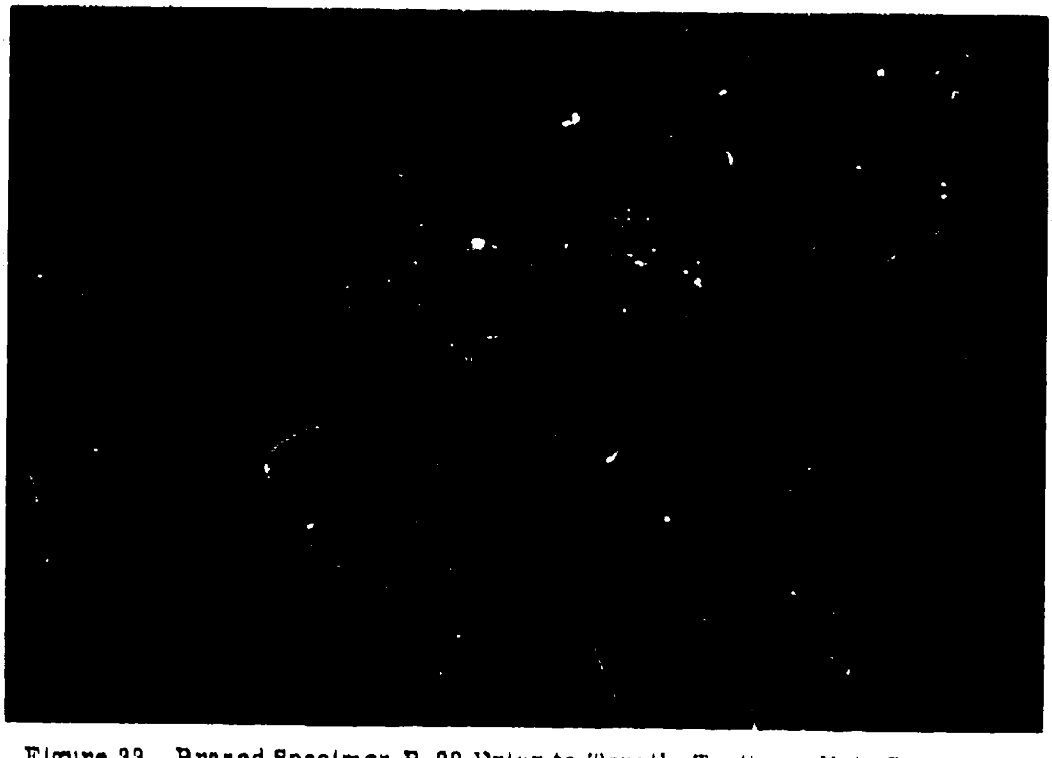

Figure 33 Brazed Specimen B-22 Prior to Tensile Testing. Note Separation of Braze (arrow) From Parent Metal. (Environmental-test conditions: 800F, 117 ksi, salt; duration: 63 cycles) (H-63820)
Mag: 15X

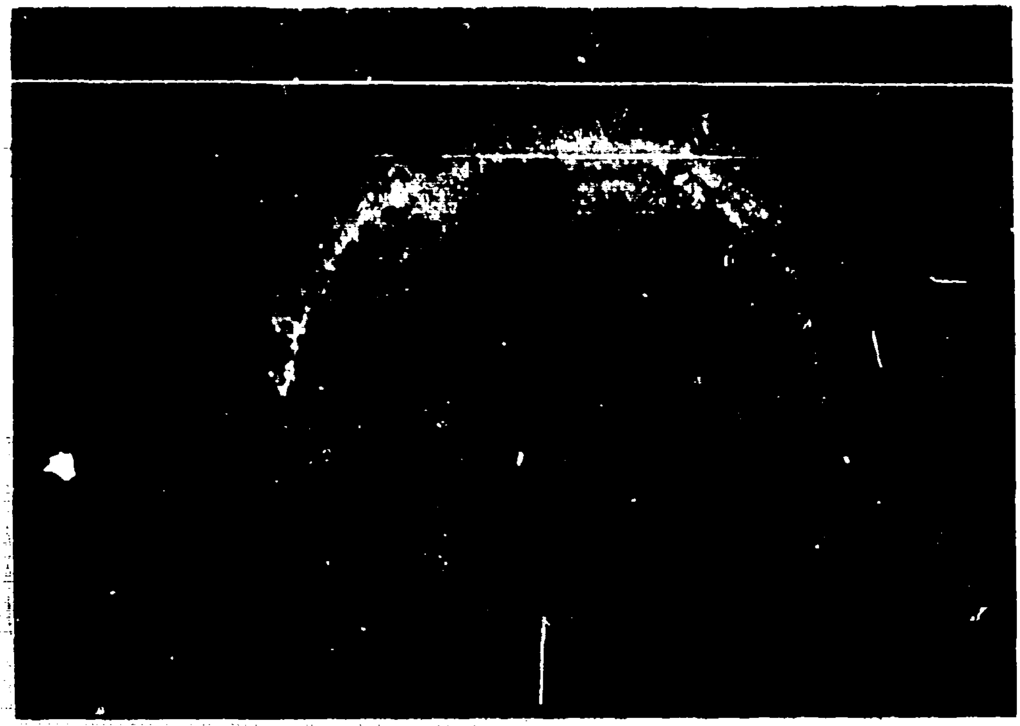

Figure 34 Brazed Specimen B-23 Prior to Tensile Testing. Note Separation of Braze (arrow) From Parent Metal. (Environmental-test conditions: 600F, 130 ksi, salt; duration: 63 cycles) (H-63827)
Mag: 15X

PH15 - 7Mo (Welded) - Tables XVIII and XV summarize the environmental-test history for specimens of this material. All specimens showed an increase in strength after environmental exposure, the higher test temperature resulting in the greatest strength increase and also an increase in hardness; no degradation due to the applied salt was apparent and no instance of Type-(1) and Type-(3) corrosion cracking was found. Joining decreased the strength after high-temperature exposure.

PH15 - 7Mo (Brazed) - Table XVIII indicates that there were four brazed specimens, two with salt patches (C-21, C-24) and two without (C-29, C-30), which experienced corrosion. One of these (C-30) failed about ten cycles prior to its scheduled 63 cycles; the others completed their scheduled cyclic testing. Three were cycled to 800 F and one (C-24) was cycled to 600 F (but at the upper value of stress). Salted specimen C-21 exhibited low ductility when pulled in tension. Failure occurred out of the brazed area but within the salt patch (Figure 35). Examination of its fracture surfaces following tensile test revealed a small discolored region at the origin of fracture (Figure 36). Salted specimen C-24 showed evidence of localized discoloration on its fracture surfaces following tensile test. The fracture originated in the discolored region, which was at the edge of the specimen and away from the salt coating. The corrosion was in a region which had apparently been stained by a material known as "Green Stop-off". The arrow in Figure 37 points to the origin. This material had been applied in order to restrict braze flow during preparation of the specimen. Additional cracks were present in this stained area and are shown in Figures 38 and 39.

TABLE XVIII

ENVIRONMENTAL-TEST HISTORY: PH15 - 7Mo ALLOY SPECIMENS

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Figure 35 Brazed Specimen C-21 After Tensile Test, Showing Location of Rupture. (Environment-test conditions: 800F, 130 ksi, salt; duration: 63 cycles) (EP-2172-11)
Mag: 20X

Figure 36 Brazed Specimen C-21 After Tensile Test. Arrow Points to Crack at Fracture Origin. (Environment-test conditions: 800F, 130 ksi, salt; duration: 63 cycles) (H-64394)
Mag: 24X

Figure 37 Brazed Specimen C-24 After Tensile Test. Arrow Points to Discoloration on Fracture Surface. (Environmental-test conditions: 600F, 160 ksi, salt; duration: 68 cycles) (H-64895) Mag: 24X

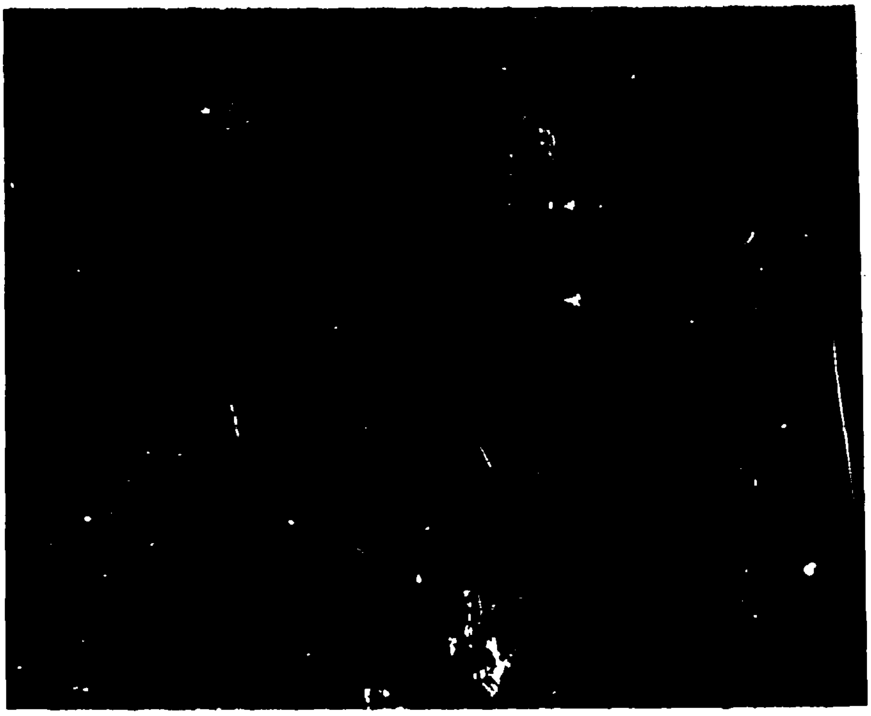

Figure 38 Brazed Specimen C-24 After Tensile Test. Arrows Point to Cracks in Dark Stained Areas. (Environmental-test conditions: 600F, 160 ksi, salt; duration: 63 cycles) (H-64891) Mag: 15X

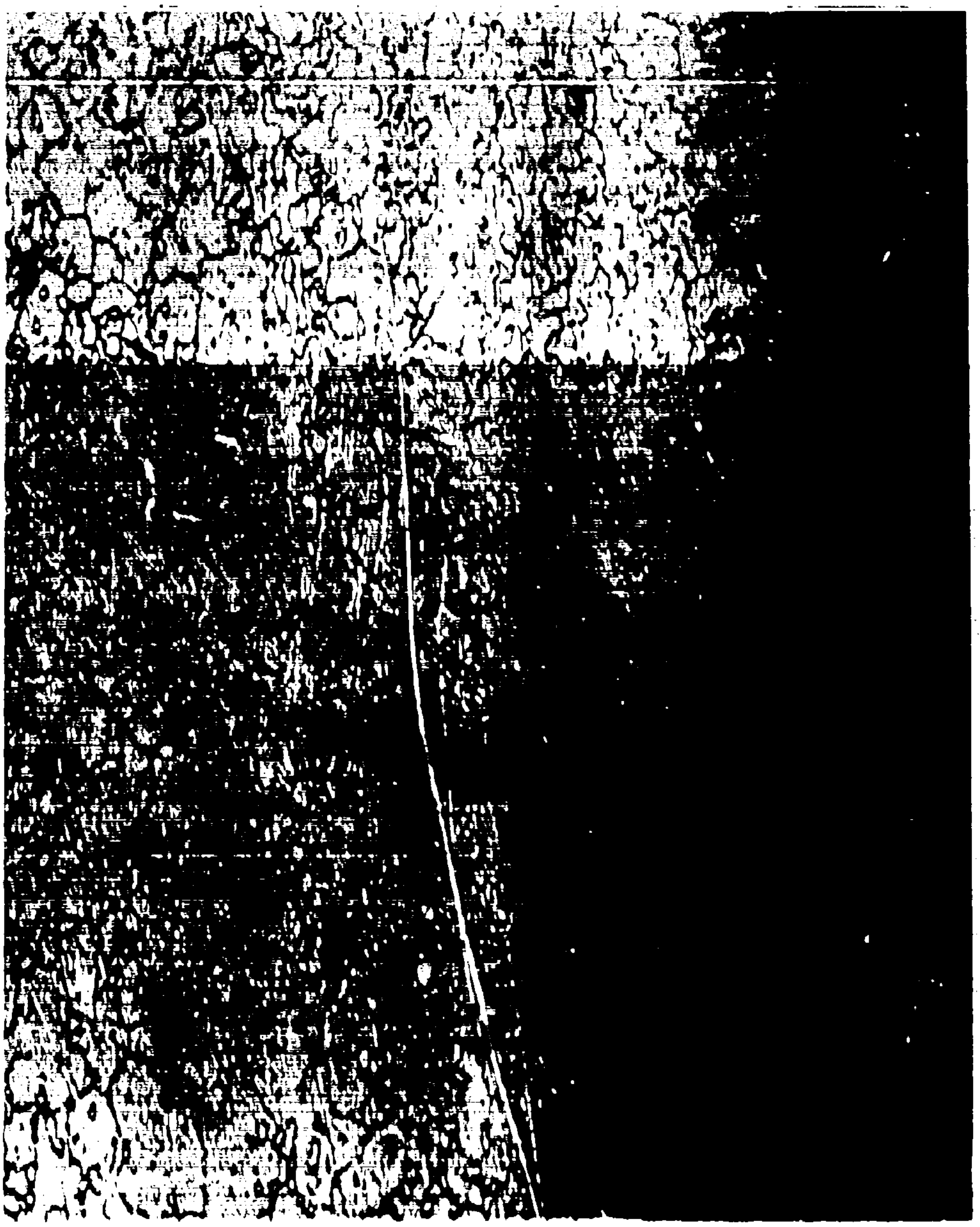

Figure 30 Brazed Specimen C-24 After Tensile Test. Photomicrograph Through Crack in Dark Stained Area Shown in Previous Figure. (Environmental-test conditions: 600F, 160 ksi, salt; duration: 63 cycles) (EP-2210-8)

Etchant: Villela's Reagent Mag: 500X

The fracture surfaces of the two unsalted specimens (C-29 and C-30) which also experienced corrosion appear in Figures 40 and 41, dark discolored regions being indicated by arrows. The corrosion cracks, but not the fractures, had their origins in those regions, which again were in the area of the application of Green Stop-off. The dark regions also contained numerous irregular cracks aligned parallel to and adjacent to the fracture surfaces, as can be seen in Figures 42, 43, and 44. Specimen C-29 failed away from the brazed area (Figure 45) in post-exposure tensile testing, while C-30 failed in the braze during environmental testing (Figure 46).

Figure 40 Brazed Specimen C-29 After Tensile Test. Arrow Points to Discoloration on Fracture Surface. (Environmental-test conditions: 800F, 130 ksi, no salt; duration: 63 cycles) (H-64896, Mag: 24X

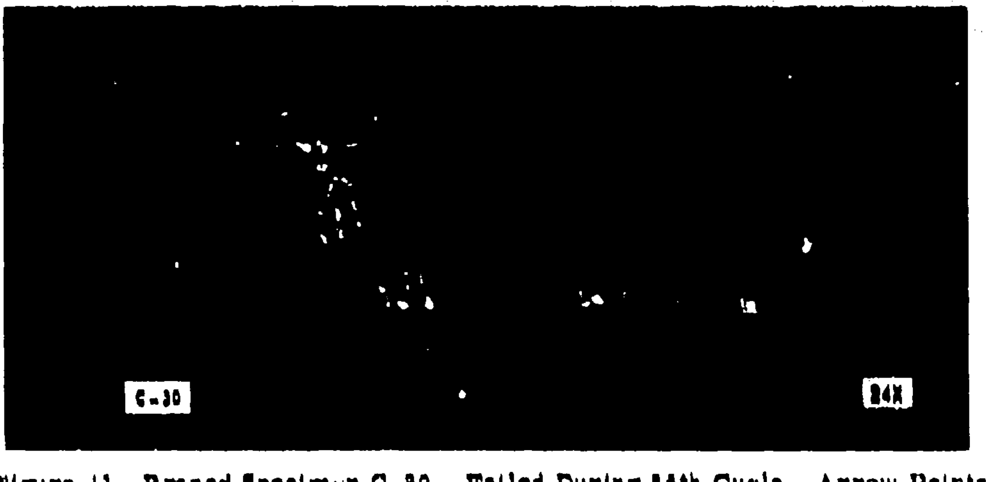

Figure 41 Brazed Specimen C-30. Failed During 55th Cycle. Arrow Points to Discoloration on Fracture Surface. (Environmental-test Conditions: 800F, 130 ksi, no salt; scheduled duration: 63 cycles) (H-64807) Mag: 24X

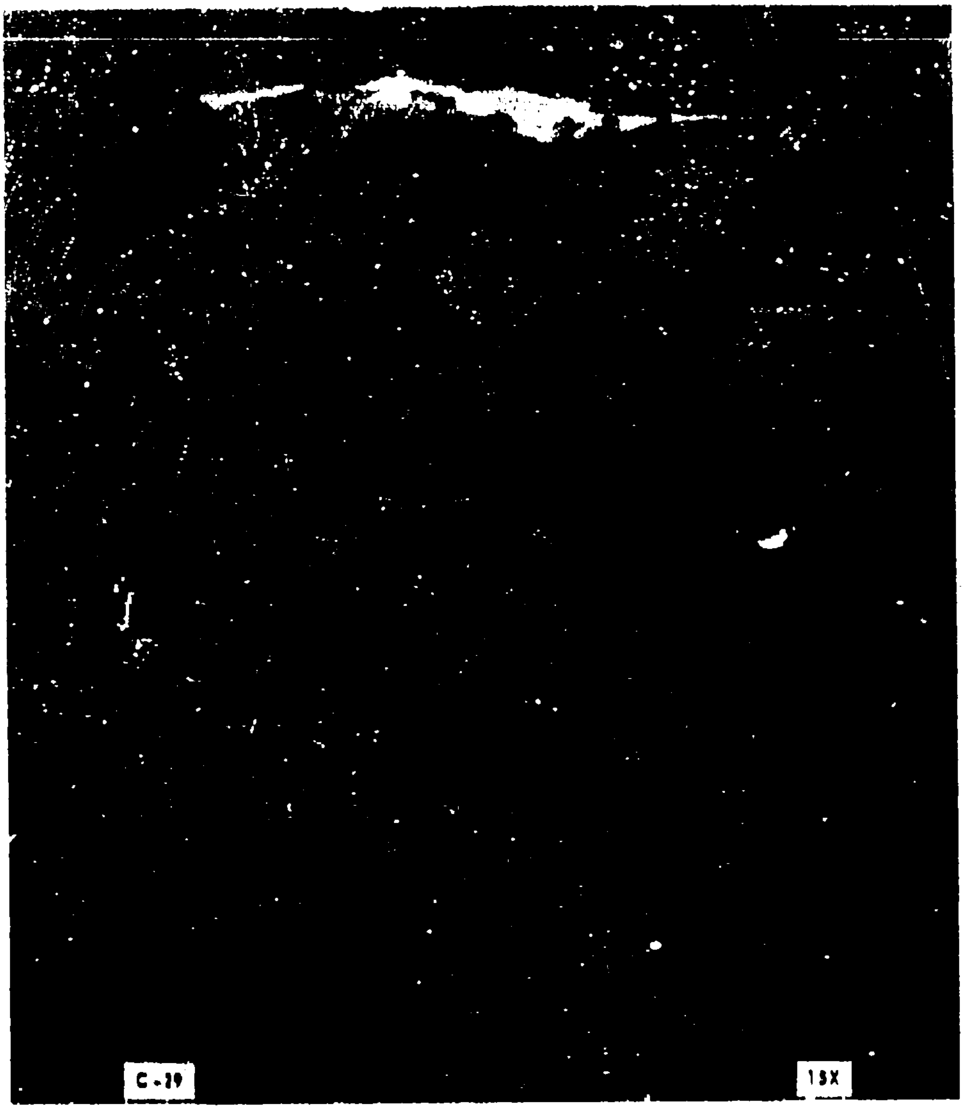

Figure 42 Brazed Specimen C-29 After Tensile Test. Arrow Points to One of the Cracks in the Stained Area. (Environmental-test conditions: 800 F, 130 ksi, no salt; duration: 63 cycles) (H-64892)
Mag: 15X

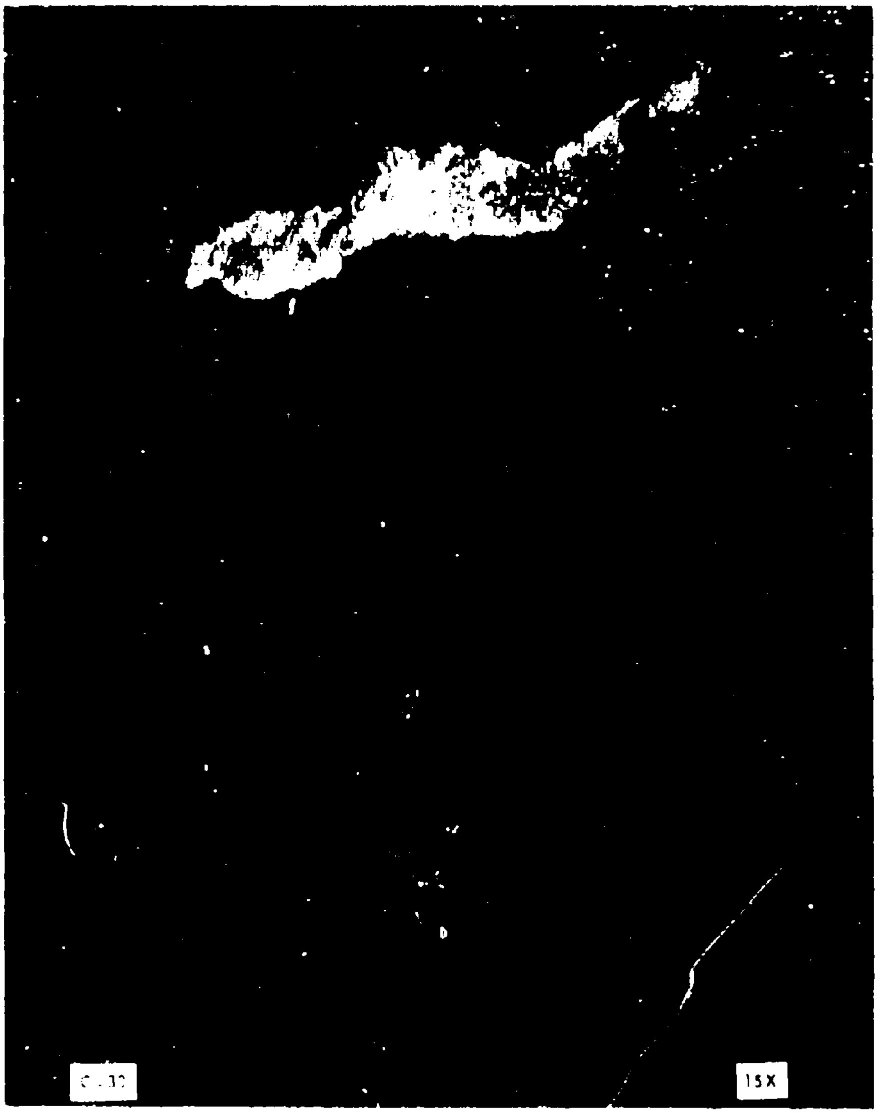

Figure 43 Brazed Specimen C-30. Failed During 53th Cycle. Arrows Point to Cracks in the Stained Area. (Environmental-test conditions: 800F, 130 ksi, no salt; scheduled duration: 63 cycles) (H-64893)
Mag: 15X

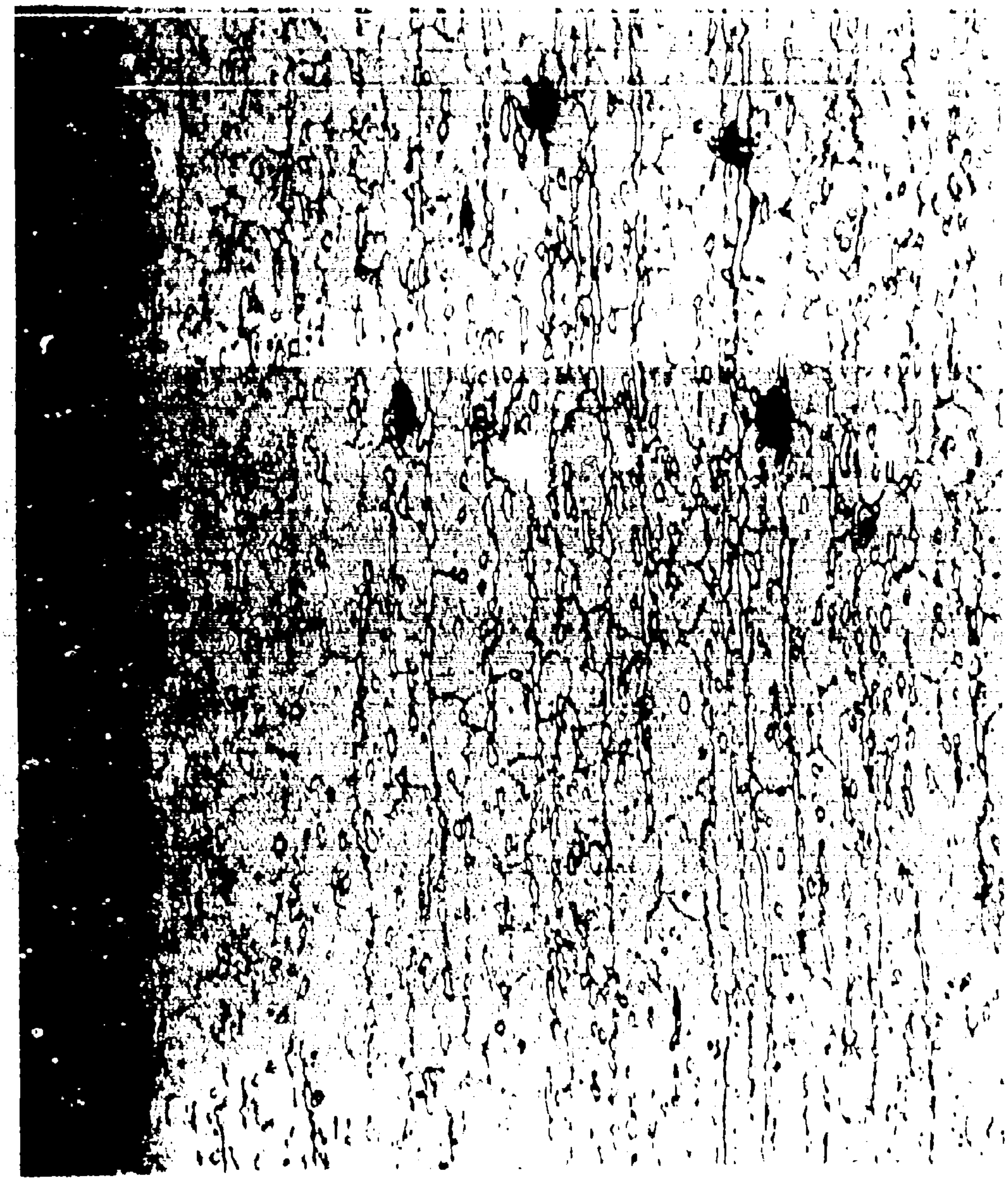

Figure 44 Brazed Specimen C-30. Failed During 55th Cycle. Photomicrograph Through Cracks in Stained Area Shown in Previous Figure. (Environmental-test conditions: 800F, 130 ksi, no salt; scheduled duration: 63 cycles) (EP-2168-7)

Etchant: Villela's Reagent Mag: 500X

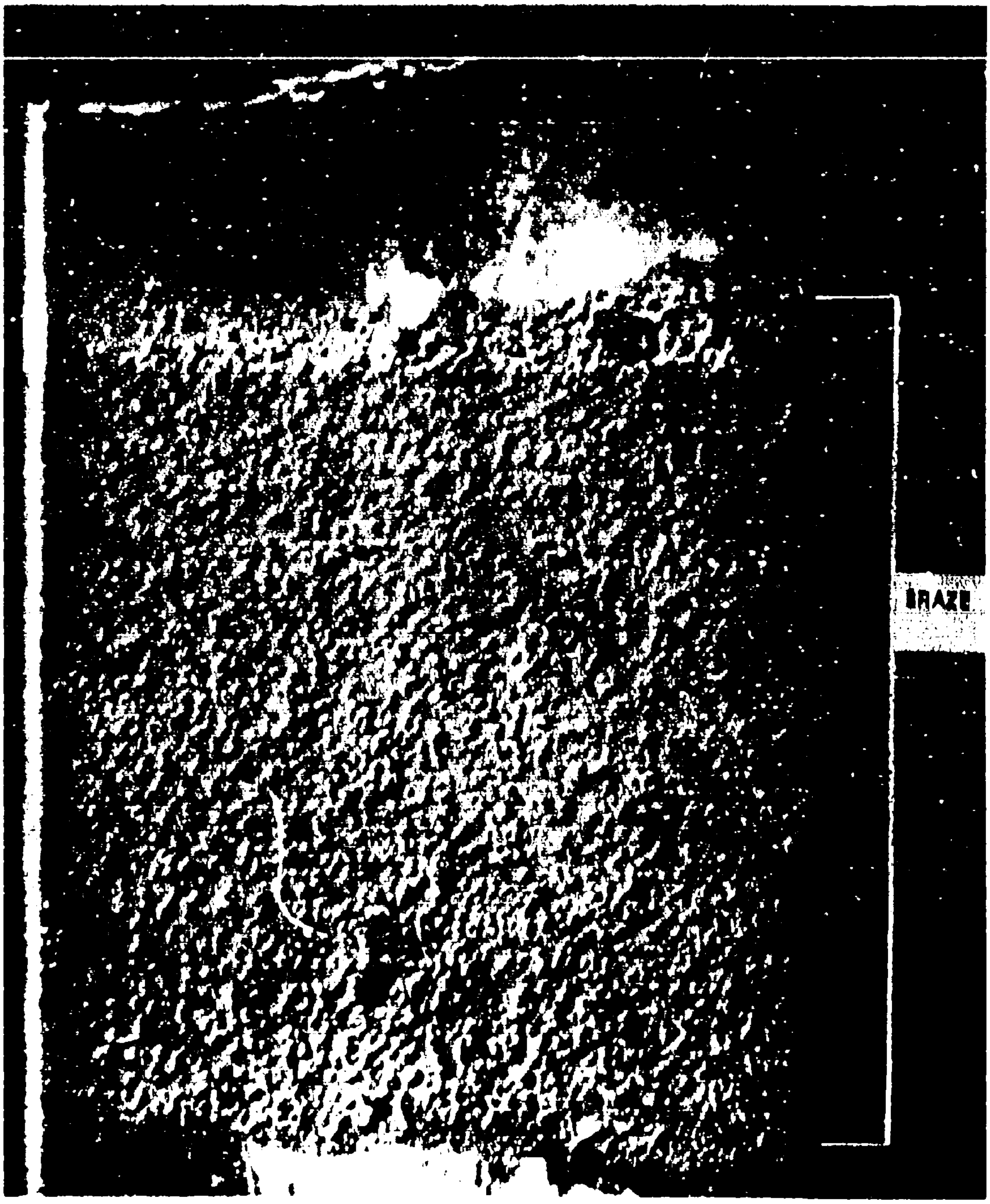

Figure 45 Brazed Specimen C-29 After Tensile Test, Showing Location of Rupture. (Environmental-test conditions: 800F, 130 ksi, no salt; duration: 63 cycles) (EP-2172-10)
Mag: 10X

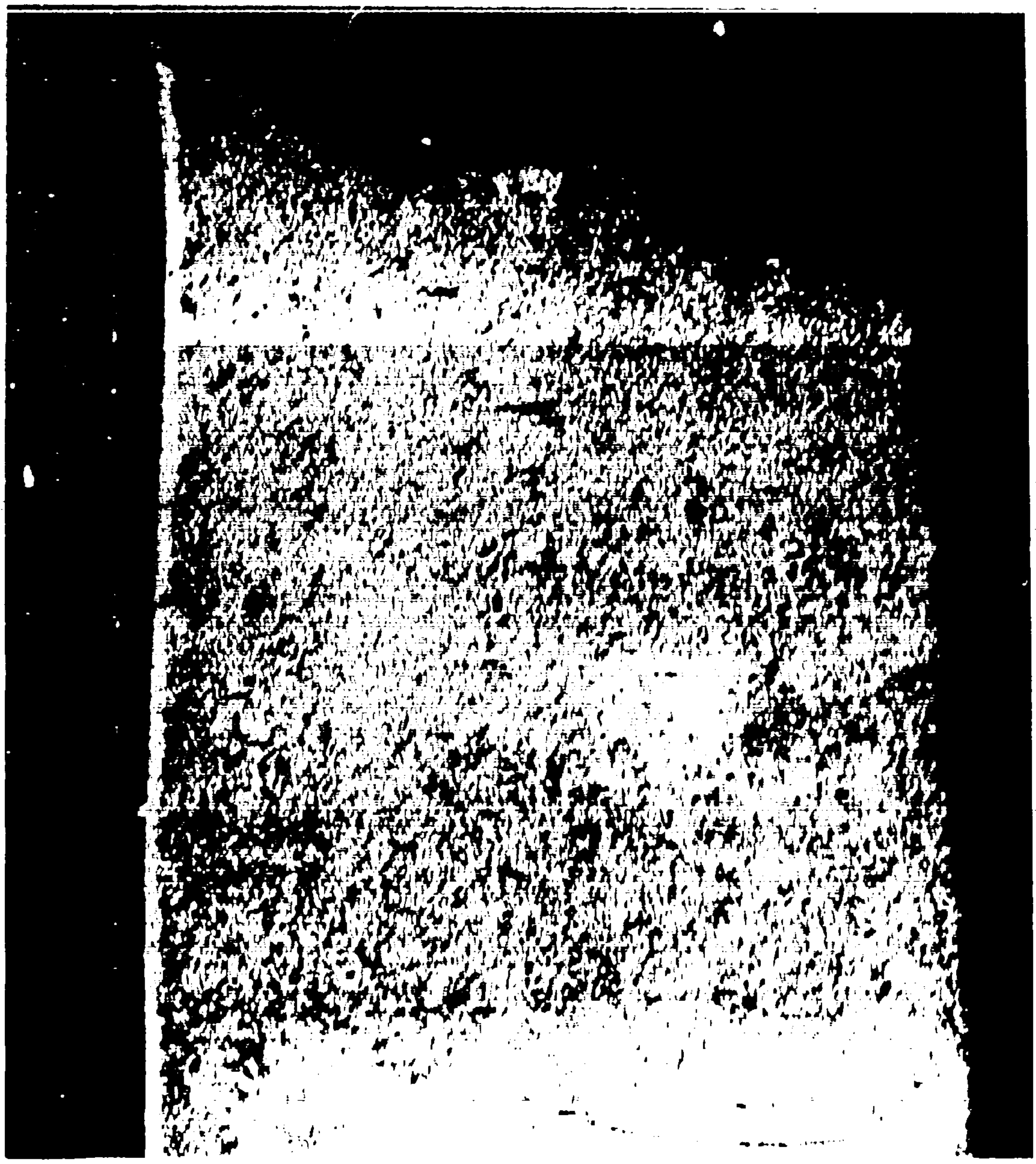

Figure 40 Brazed Specimen C-30, Showing Location of Failure. Failed During 55th Cycle. (Environmental-test conditions: 800F, 130 ksi, no salt; scheduled duration: 63 cycles) (EP-2172-0)
Mag: 10X

Green Stop-off is a proprietary commercial product. Chemical analysis of a sample indicated that it contained no fluorides or sulphates and only a trace of chlorides. It was slightly acidic (pH 5.4). A qualitative spectrographic analysis made on a sample revealed that it was high in titanium and contained trace amounts of aluminum and silicon. The manufacturer's literature indicated that the material had a lacquer base. Although the analysis did not disclose the presence of any constituents which were deemed to be conducive to corrosion, it is not known if the Green Stop-off influenced the corrosion which was observed.

The tensile strengths obtained for the two non-brazed control specimens (C-39 and C-40) after exposure to 800 F were approximately the same, even though one was salted. This would indicate that the salt alone had no effect on base-metal properties. In addition, the strengths of the non-brazed control specimens were considerably greater than those of the brazed specimens measured after exposure to 800-F conditions.

An unexposed braze specimen (C-36), when tensile tested at room temperature, was found to have tensile strengths comparable to those of specimens exposed to the 600-F-temperature conditions. As was the case for welded and brazed AM-350 and AM-355 and welded PH15 - 7Mo specimens discussed earlier in this subsection, the higher strengths were attributed to the additional aging which occurred during elevated-temperature exposure. Tables XVIII and XV indicate that corrosion effects, not necessarily attributable to salt, lowered the strength at 800 F, but not at 600 F. High temperature increased the strength at high cycles. No effect of cycling was found at low temperature. Joining decreased the strength after exposure.

<u>PH14 - 8Mo (Welded)</u> - Tables XIX and XV summarize the environmental-test history for specimens of this material. There were no instances of specimen failure during cyclic testing, nor were there any indications of corrosion cracking when specimens were examined following post-exposure tensile test. As was experienced with the three previously discussed alloys, additional elevated-temperature aging resulted in noticeable strength increases. Salt had no apparent effect on the alloy in its welded form. Welding did not affect the strength with exposure.

TABLE XIX

ENVIRONMENTAL-TEST HISTORY: PH14 - 8Mo ALLOY SPECIMENS

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PH14 - 8Mo (Brazed) - A situation somewhat analogous to that observed during the investigation of brazed specimens of PH15 - 7Mo alloy was found to exist with brazed specimens of PH14 - 8Mo alloy. Reference to Table XIX indictates that, of the 14 specimens (12 brazed and two non-brazed for controls), nine failed during cyclic exposure. The five specimens (D-24, D-27, D-28, D-35 and D-36) which completed their scheduled number of cycles had been subjected to the 600-F temperature level; none of these was observed to have corrosion cracks on examination following post-exposure tensile testing and cycling increased the strength at this temperature. Of the nine specimens which failed during cyclic testing, all but one (D-23) had been subjected to the

800-F temperature level and four (D-21, D-29, D-30, and D-34) experienced corrosion cracks. Therefore, no comparison can be made of the strengths at this temperature. Two of the latter group were salted (D-21 and D-34), two were unsalted (D-29 and D-30), and all four had failed in less than two cycles of exposure at 800 F and had many irregular cracks. The cracks were parallel to the fracture surfaces, as shown in the photographs of specimens D-21 and D-30, Figures 47, 48, 49, and 50, and were confined to a region which was discolored, apparently by Green Stop-off. Shallow, blue discolorations were observed on the peripheries of the fracture surfaces (Figures 51 and 52). There were no surface cracks or discolorations on the fracture surfaces of the two unbrazed specimens (D-39 and D-40) which had also failed prematurely (in less than two cycles). All fractures were of a ductile-shear nature and none originated at the shallow discontinuities which were observed. From the several findings which have been referred to, the conclusion was reached that the crack indications were of the corrosion type, although not necessarily attributable to applied salt since unsalted specimens showed similar cracks. It was further concluded that the premature failures could not be attributed to the presence of incipient corrosion cracks inasmuch as a non-brazed, unsalted, control specimen (D-39) had also failed prematurely, as previously mentioned. As was found for the brazed PH15 - 7Mo specimens, evidence of corrosion was apparent in both salted and unsalted samples, thus preventing evaluation of salt effect alone.

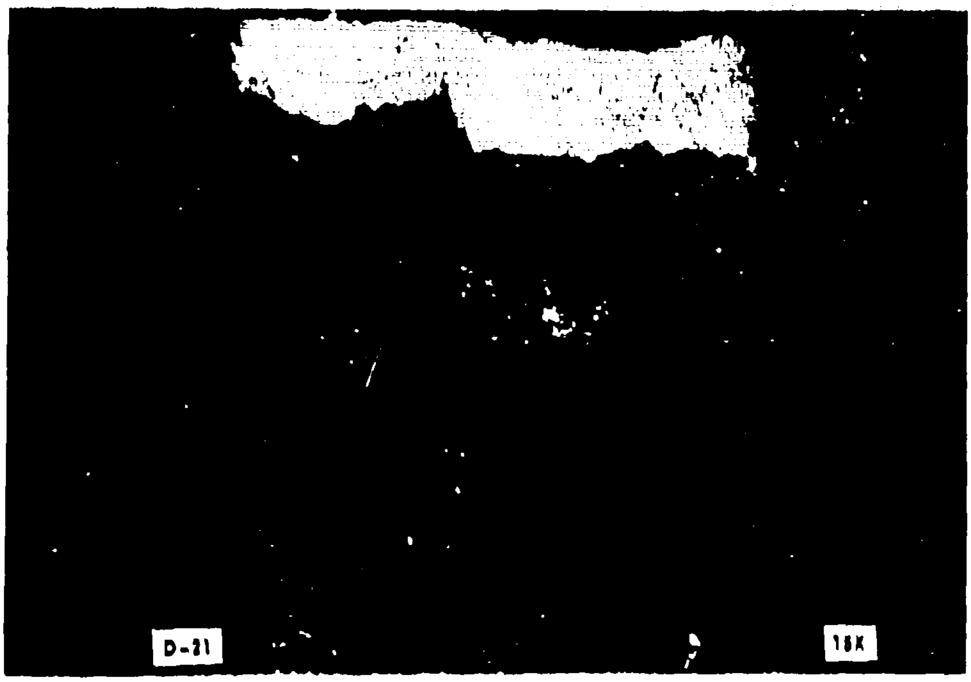

Figure 47 Brazed Specimen D-21. Failed During 2nd Cycle. Arrow Points to Crack. (Environmental-test conditions: 800F, 148 ksi, salt; scheduled duration: 63 cycles) (H-63829)
Mag: 15X

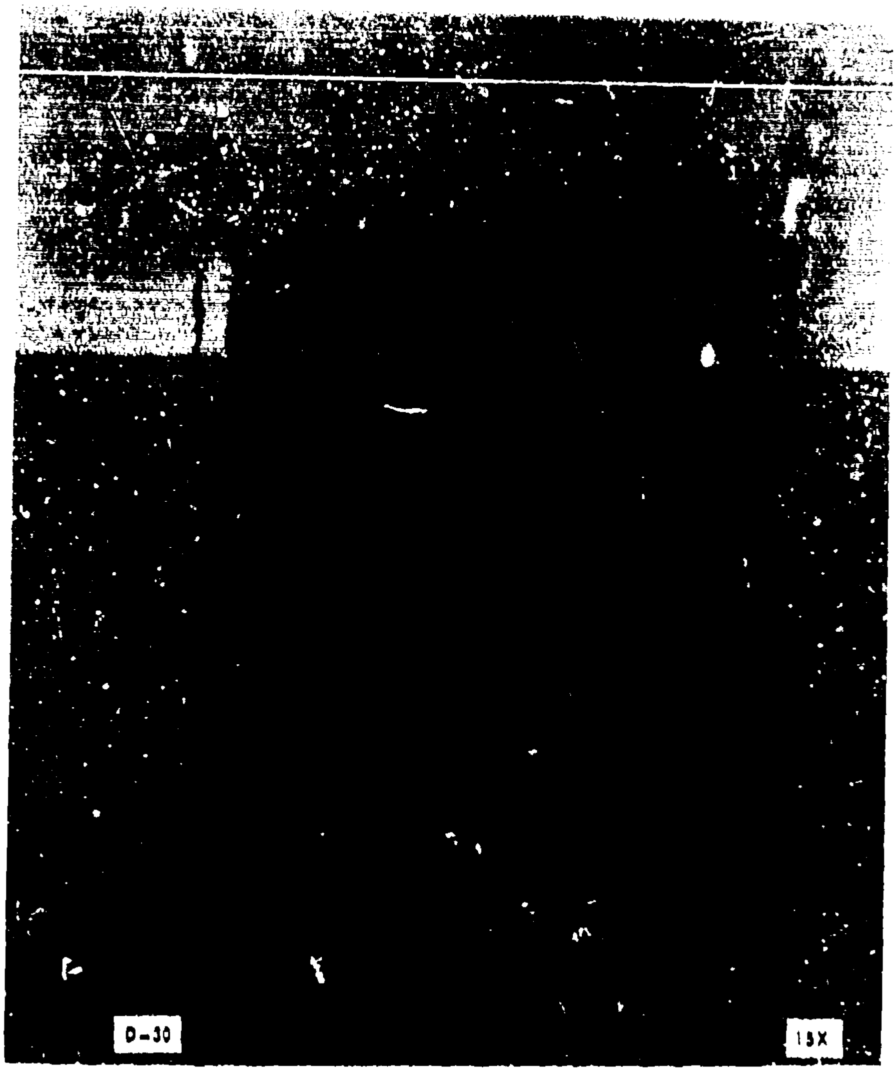

Figure 48 Brazed Specimen D-30. Failed During 1st Cycle. Cracks Confined to Stained Regions (indicated by brackets) on Side Opposite Braze. (Environmental-test conditions: 800F, 149 ksi, no salt; scheduled duration: 63 cycles) (H-64516)
Mag: 15X

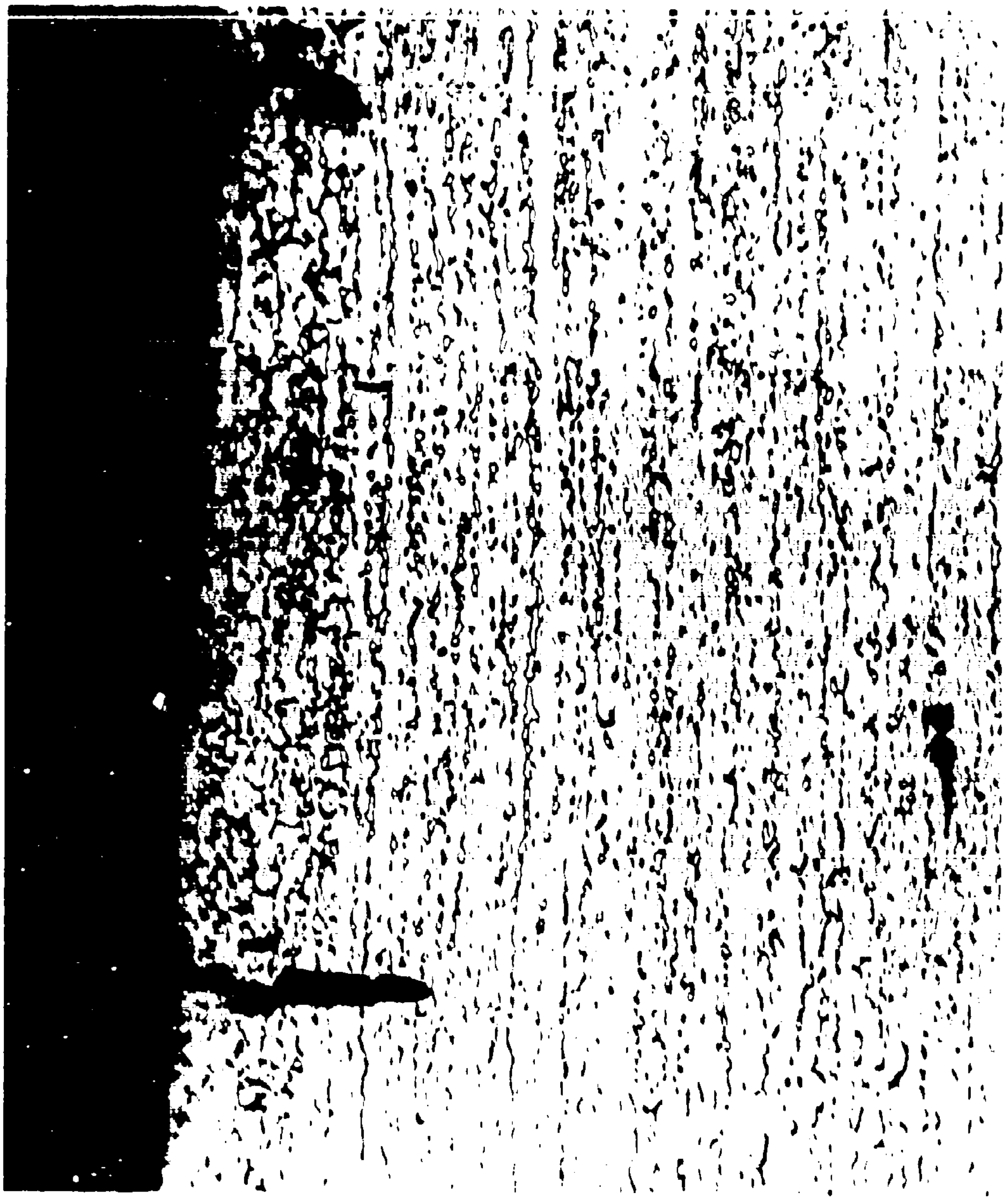

Figure 49 Brazed Specimen D-20. Failed During 2nd Cycle. Photomicrograph Through Cracked Area. (Environmental-test conditions: 800F, 148 ksi, no salt; scheduled duration: 63 cycles)

(EP-2219-D)

Etchant: Villela's Reagent Mag: 500X

Figure 50 Brazed Specimen D-30. Failed During 1st Cycle. Photomicrograph Through Cracked Area. (Environmental-test conditions: 800F, 148 ksi, no salt; scheduled duration: 63 cycles)

(KP-2108-10)

Etchant: Villela's Reagent Mag: 500X

Figure 51 Brazed Specimen D-34. Failed During 2nd Cycle. Arrows Point to Discolorations on Fracture Surface. (Environmental-test conditions: 800F, 148 ksi, salt; scheduled duration: 10 cycles) (H-64818) Mag: 24X

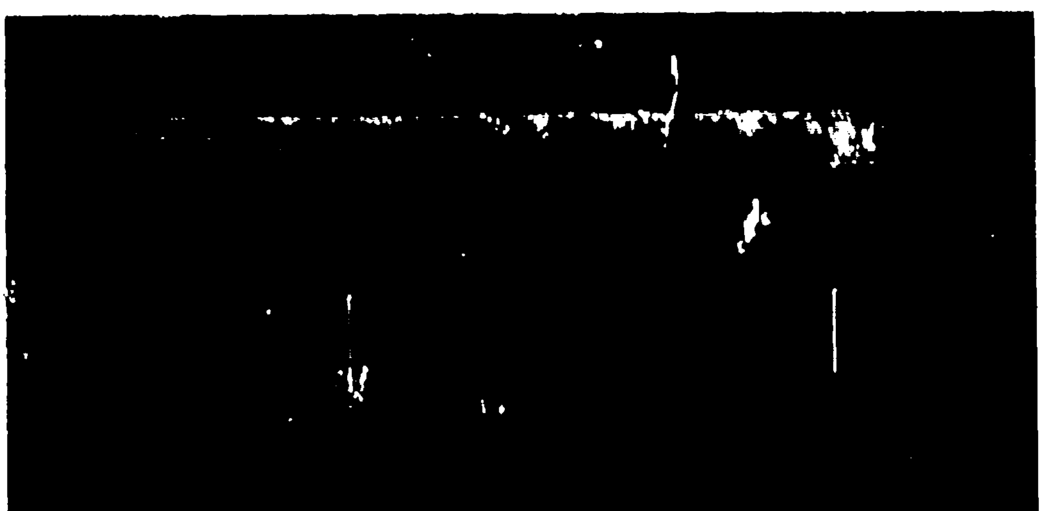

Figure 52 Brazed Specimen D-30. Failed During 1st Cycle. Arrows Point to Discolorations in Fracture Surface. (Environmental-test conditions: 800F, 148 ksi, no salt; scheduled duration: 03 cycles) (H-64817) Mag: 24X

An explanation was sought as to why the welded specimens had survived their scheduled cyclic testing whereas the brazed specimens had not. The two non-welded control specimens (D-19 and D-20) had been fabricated from the same lot of material from which the two non-brazed control specimens (D-39 and D-40) had been fabricated, yet the non-welded specimens successfully completed 63 cycles under the same exposure conditions as the non-brazed specimens had been exposed to, 800F and 148 ksi. The heat treatments for the two pairs of controls were different (the braze controls had been exposed to the 1700-F portion of the heat-treat cycle in vacuum), but the material hardnesses were determined to be comparable: Rockwell C 47 for weld controls, Rockwell C 46 for braze controls. However, as shown in Table XX, the 800-F yield strengths of unexposed welded and brazed specimens were quite different, both being below "typical" values reported in the literature. The lower strengths of the welded specimens were attributed to the weld joint. The lower strength of the brazed PH14 - 8Mo material was attributed to the slower cooling rate in the vacuum-brazing process. Thus, the brazed specimens which were exposed at 800F and 148 ksi were stressed approximately twenty-five per cent above their actual yield strength, accounting for the premature failures.

TABLE XX

COMPARISON OF MECHANICAL PROPERTIES OF TWO UNEXPOSED WELDED AND TWO UNEXPOSED BRAZED SAMPLES OF PH14 - 8Mo MATERIAL
(Based on tensile tests at 800F)

Sample No.	Joint	Condition	UTS (ksi)	0.2% YS (ksi)	El (%)
D-12	Weld	SRH-950	165	136	6
D-13	Weld	SRH-950	169	139	6
D-31	Braze	SRH-950	160	115	10
D-32	Braze	SRH-950	159	132	11
*DMIC Rpt. 223		SRH-950	180	153	8

*Defense Metals Information Center Report 223, January 3, 1966, Battelle Memorial Institute, Columbus, Ohio 43201

Hastelloy X (Welded) - Table XXI summarizes the environmental-test history for specimens of this material. All specimens which were cycled at 1600F completed their scheduled number of cycles without failure. When they were subsequently tensile tested at room temperature and their fracture surfaces were examined, there was no evidence of salt corrosion. No significant differences in tensile strengths due to cycling were evident, for the specimens which were exposed at 1600F. Strengths were slightly higher and ductilities were lower, compared to those properties for unexposed material. Increased hardness values correlate with the higher observed strengths.

TABLE XXI

ENVIRONMENTAL-TEST HISTORY: HASTELLOY-X ALLOY SPECIMENS

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[illegible]	Weld	Yes	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Weld	Yes	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Weld	Yes	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Weld	Yes	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Weld	No	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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[illegible]	Weld	Yes	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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However, of the eight test articles (six specimens and two controls) which were subjected to a temperature of 2000F, seven failed before completing their schedules and one failed during preliminary tensile loading. The failures were typical ductile stress-rupture breaks, as can be seen from the photograph of specimen E-6, Figure 53. Metallographic examination of salted and unsalted specimens revealed no significant difference in the degree of cracking (Figure 54), indicating that salt had little, if any, effect on rupture life. There was no evidence of corrosion in any of the specimens tested at 2000F. This temperature at applied stresses was too severe for this alloy.

Figure 53 Welded Specimen E-6. Failed During [illegible] Cycle. Failure Occurred Outside of Weld Region. Note Reduced Gage Section Above and Below Marked Weld Region. (Environmental-test conditions: 2000F, 2ksi, salt; scheduled duration: 19 cycles) (H-64085) Mag: 4.6X

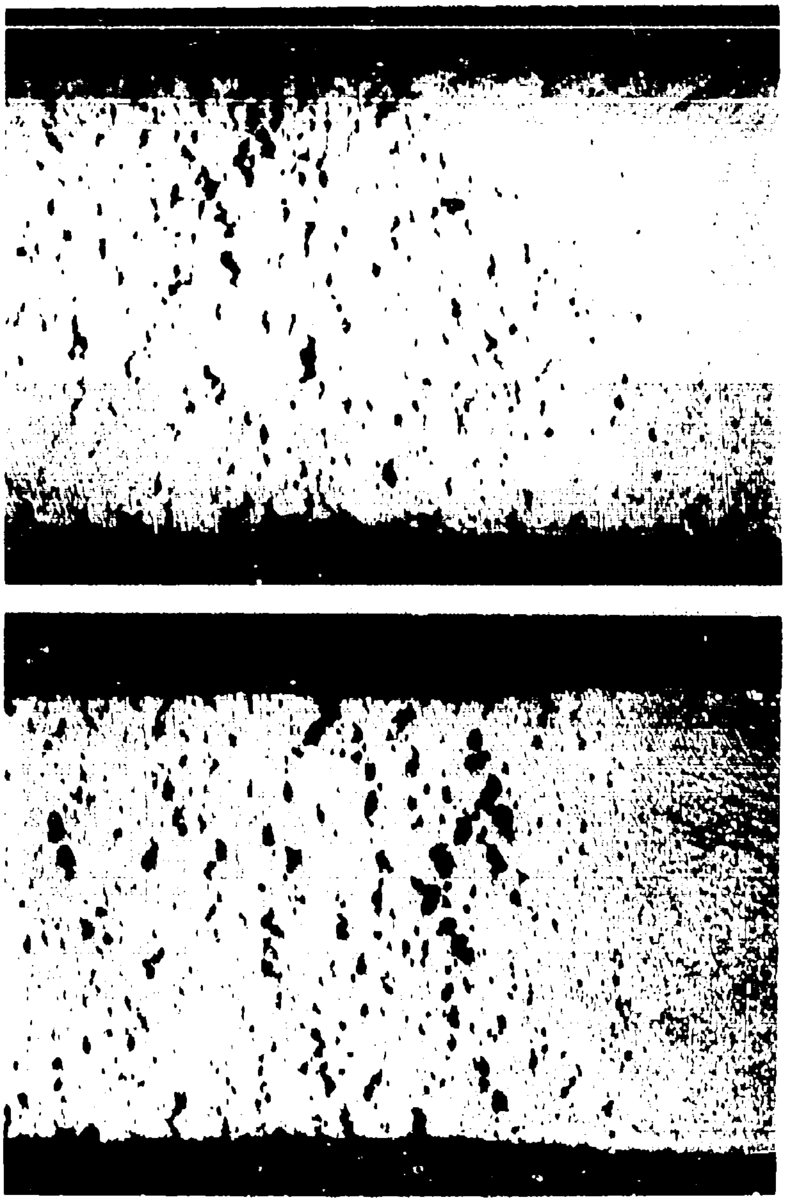

Figure 54 Photomicrographs of Welded Specimens E-1 (top) and E-14 (bottom) Specimen E-1 Ruptured in 50 cycles, E-14 Survived 63-Cycle Exposure. (Environmental-test conditions: 2000F, 1 ksi, E-1 with salt, E-14 without salt; scheduled duration: 63 cycles)

Etchant: 10% Oxalic (EP-2235- [illegible]
(EP-[illegible]
(Mag [illegible]

Hastel' ((Brazed) - No evidence of Type-(1) or Type-(3) corrosion in any of the d specimens was detected. However, as Tables XXI and XV indicate, salt did decrease the ultimate strength and ductility of this alloy at both temperatures. At the scheduled inspection of 2000-F specimens after 40 cycles of environmental testing, it was observed that very little braze metal remained on the salted material. The photographs, Figures 55 and 56, show a typical salted specimen (E-21) with only a small region of braze material left after exposure at 2000F for 40 cycles, and an unsalted specimen (E-29) exposed under the same conditions. There was no apparent reduction in braze area on those specimens which were tested at 1600F.

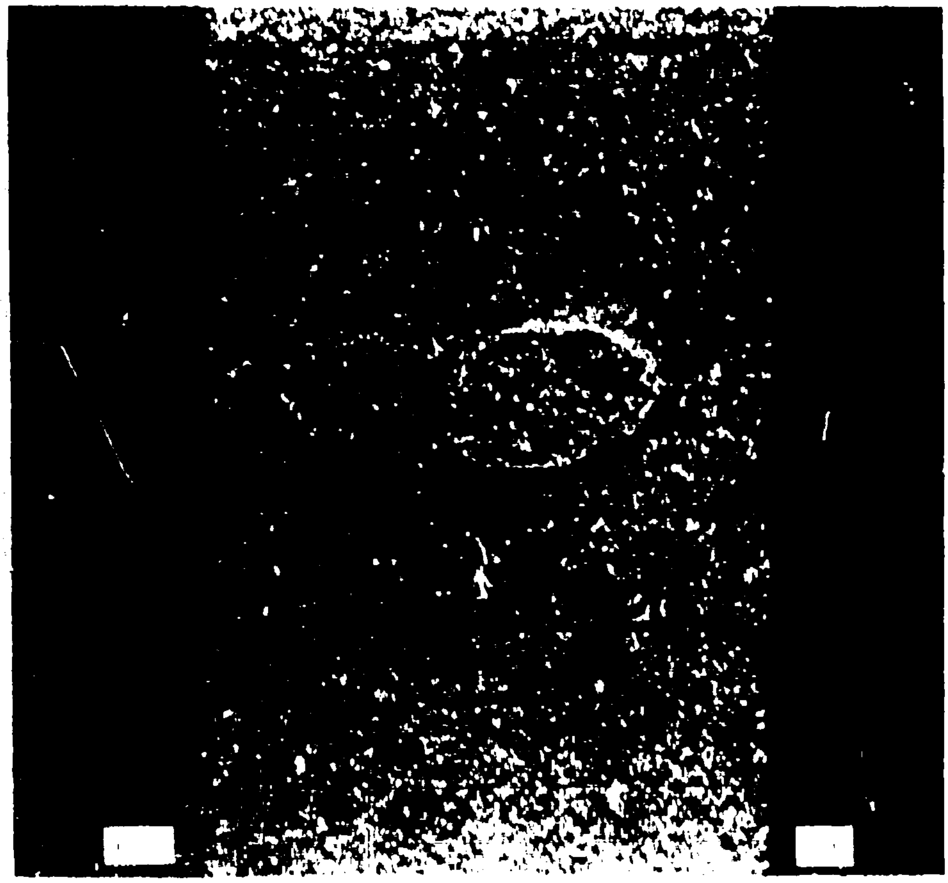

Figure 55 Brazed Specimen E-21. Testing Terminated After 40 Cycles. Remains of Braze on Surface. (Environmental-test conditions: 2000F, 1 ksi, salt; scheduled duration: 63 cycles) (H-03833) Mag: 15X

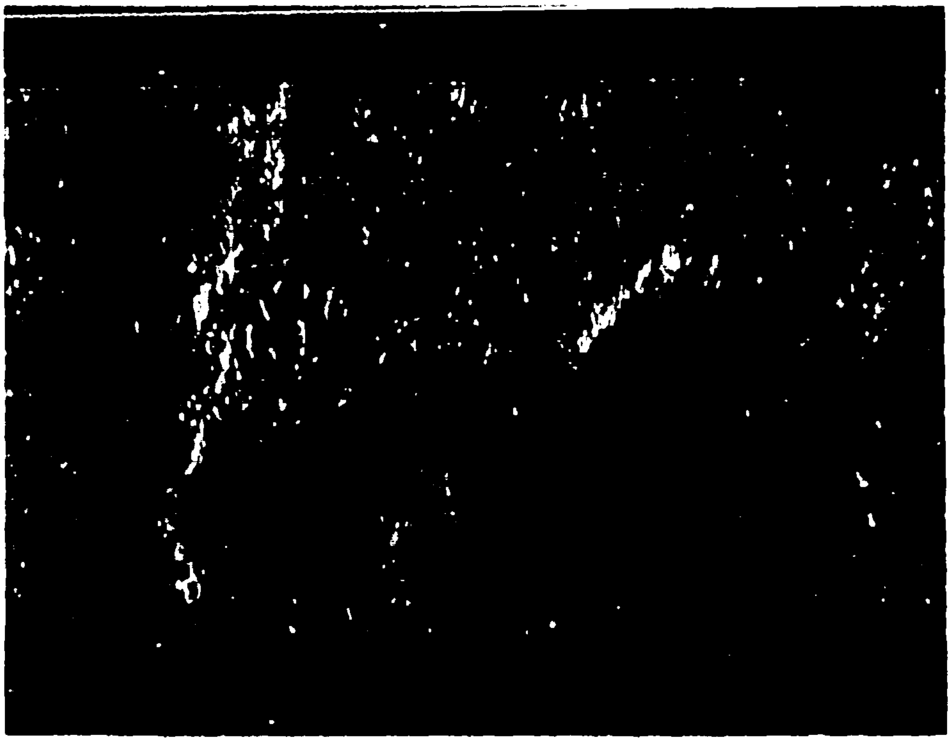

Figure 56 Brazed Specimen E-29. Testing Terminated After 40 Cycles. Significantly More Braze Material Remaining Than on Salted Specimen Shown in Previous Figure. (Environmental-test conditions: 2000F, 1 ksi, no salt; scheduled duration: 63 cycles) (H-63834) Mag: 15X

Ultimate strengths for the two brazed specimens (E-21 and E-22) exposed at 2000F for 40 cycles were 54.3 ksi and 81.5 ksi; elongations for the same specimens were 8% and 24%. Measured values of these mechanical properties for the two unsalted specimens (E-29 and E-30) were 86.4 ksi and 94.5 ksi, and 33% and 41%. The relatively low values for the salted specimens, compared to those for their unsalted counterparts, were attributed to the more extensive surface cracks (not Type-(1) or Type-(3) corrosion) which occurred in those specimens (Figure 57). Again, as Tables XXI and XV indicate, increasing temperature at high cycles and increasing cycles at low temperature decreased the strength. Exposure to salt also decreased the strength of brazed specimens. Salt appeared to affect the location of tensile failure on the specimens exposed at 2000F for 63 cycles: in the braze region for brazed and salted specimens and outside the braze region for brazed and unsalted specimens.

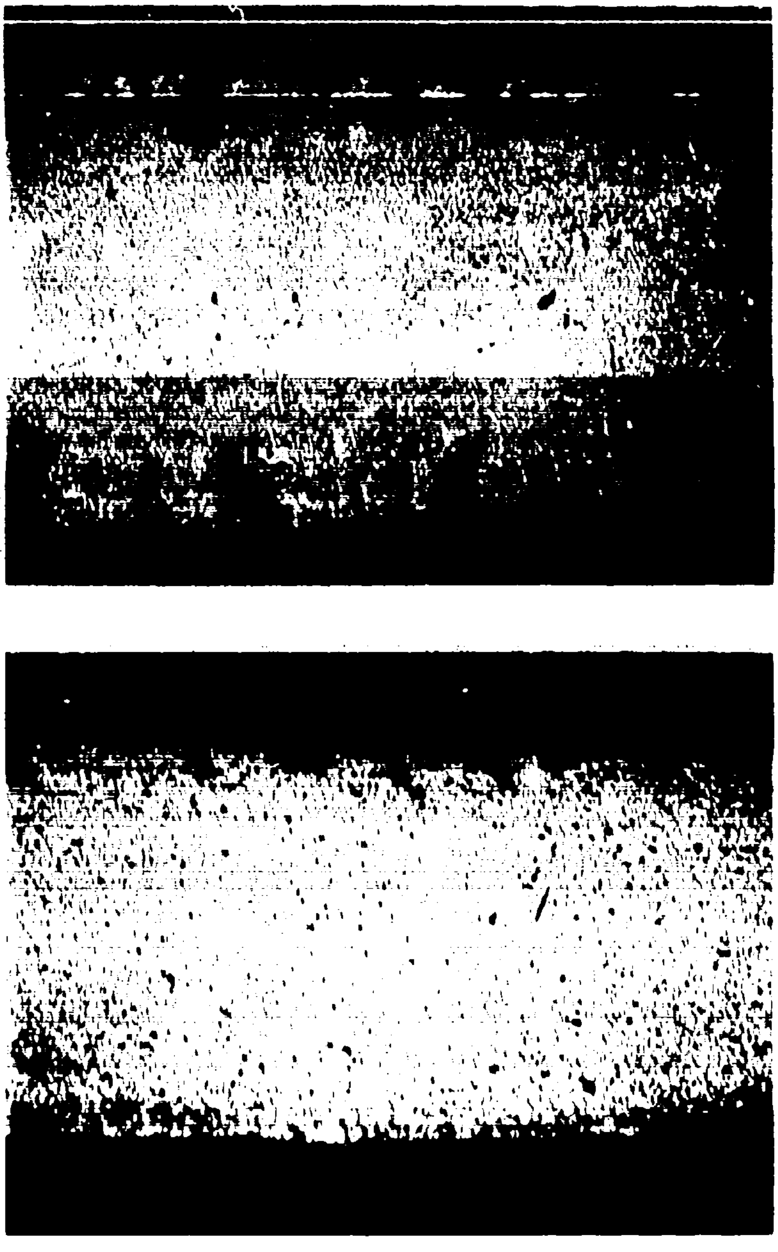

Figure 57 Photomicrographs of Brazed Specimens E-21 (top) and E-29 (bottom) After Tensile Test. Testing Terminated After 40 Cycles. (Environmental-test conditions: 2000F, 1 ksi, E-21 with salt, E-29 without salt; scheduled duration: 63 cycles) (EP-2233-1) (EP-2233-2)

Etchant: 10% Oxalic Mag: 50X

René 41 (Welded) - The strength characteristics of this material in the welded and brazed forms appear in Table XXII. It will be noted that none of the tested specimens experienced Type-(1) or Type-(3) corrosion. However, it was evident from the test experience that exposure at 1800F and 63 cycles subjected the six specimens to a very severe condition; three of the six test pieces failed in stress rupture (Figures 58, 59, 60, and 61) before completing the scheduled 63 cycles; and the tensile strengths, yield strengths, and elongations of those specimens which survived were found to have been considerably reduced. The post-exposure-hardness data in Table XXII indicate that, at 1800F, René 41 is severely over-aged. The three specimens (two unsalted) which completed their assigned 63 cycles at 1800F and 3 ksi were found to have numerous cracks (not Type-(1) or Type-(3) corrosion) along their gage lengths and outside their weld regions, the degree of cracking being greater for the salted specimen (Figure 62). As Table XXII indicates, the salted specimen (F-1) exhibited ultimate and 0.2%-yield strengths of 76.5 and 63.6 ksi; elongation was 3%. The two unsalted specimens (F-9 and F-10) exhibited ultimate and 0.2%-yield strengths in excess of 100 and 70 ksi, with an elongation of 8%. These data would suggest that the salt compromised the strength and ductility of specimen F-1. The specimens also exhibited considerable necking (reduction of area), as can be seen in Figure 63, on post-exposure tensile test; none failed through the weld. Figure 64 is a view of one fracture surface of the specimen shown in Figure 63. The dark band around its periphery was observed in salted and unsalted specimens exposed at 1800F and is oxide discoloration.

Two welded and salted specimens (F-5 and F-6) were exposed at 1800F and a stress of 4 ksi for 19 cycles. On tensile test, these showed higher values of strength than did either the salted or unsalted ones which had been tested at 1800F and 3 ksi for 63 cycles. The specimens which were tested for the shorter time and the higher stress exhibited slight cracking in their gage sections and failed through the welds when pulled to destruction. Apparently the additional 44 cycles at 1800F to which the 3-ksi-stress specimens were subjected were sufficient to cause incipient failure in the parent metal, with a resulting lowering of tensile strength.

Those salted specimens which were exposed at 1600F did not deteriorate to the extent that those exposed at 1800F did. All specimens evaluated at 1600F, salted and unsalted, suffered a significant loss in tensile strength and ductility, as evidenced by the values in Table XXII for two unexposed samples (F-16 and F-17). Thus, it was indicated that exposure at the lower temperature (1600F) also over-aged the René 41 material, although hardness-value changes were slight. However, the two salted specimens exposed at 1600F and 13 ksi for 63 cycles (F-3 and F-4) had lower tensile-property values than the two which were exposed under identical conditions, but without salt (F-11 and F-12). As Tables XXII and XV indicate, salt, temperature, and cycles degraded the material.

TABLE XXII

ENVIRONMENTAL-TEST HISTORY: RENÉ-41 ALLOY SPECIMENS

		[illegible]						[illegible]						[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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[illegible]	Braze	Yes	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
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Notes: (1) [illegible]

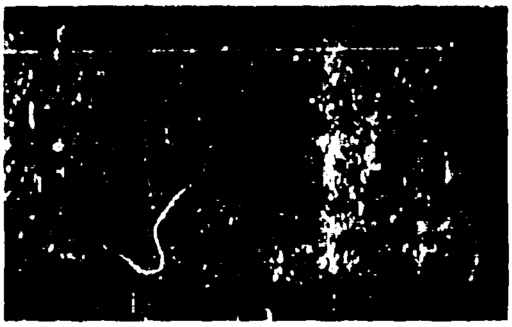

Figure 58 Welded Specimen F-2. Failed During 58th Cycle. Failure Occurred Outside of Weld (indicated by brackets). Note Extensive Stress-Rupture Cracking. (Environmental-test conditions: 1800F, 3 ksi, salt; scheduled duration: 63 cycles) (H-63835)
Mag: 7.5X

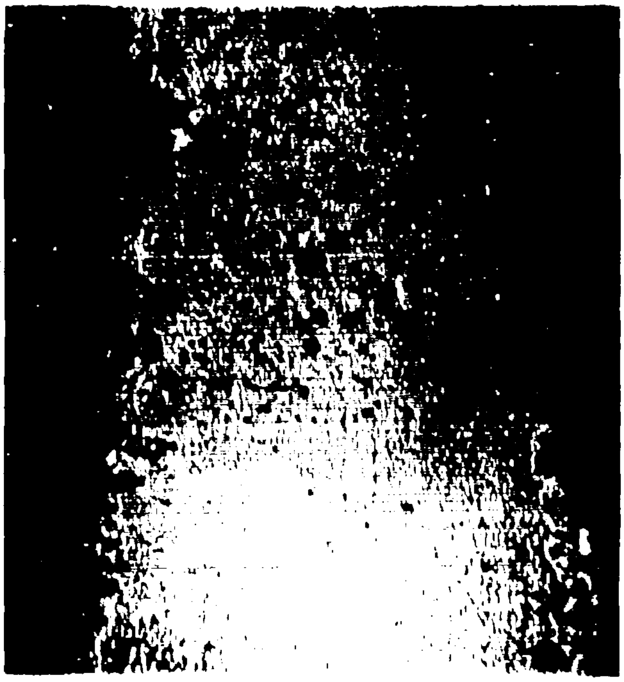

Figure 59 Welded Specimen F-2. Failed During 58th Cycle. Note Extensive Stress-Rupture Cracking. (Environmental-test conditions: 1800F, 3 ksi, salt; scheduled duration: 63 cycles) (EP-2182-5)

Etchant: 10 HNO_3 + 10 HAC + 15 HCL + 65 H_2O Mag: 50X

Figure 60 Control Specimen F-19 (no weld). Failed During 61st Cycle. Note Extensive Stress-Rupture Cracking. (Environmental-test conditions: 1800F, 3 ksi, no salt; scheduled duration: 63 cycles) (H-68836) Mag: 15X

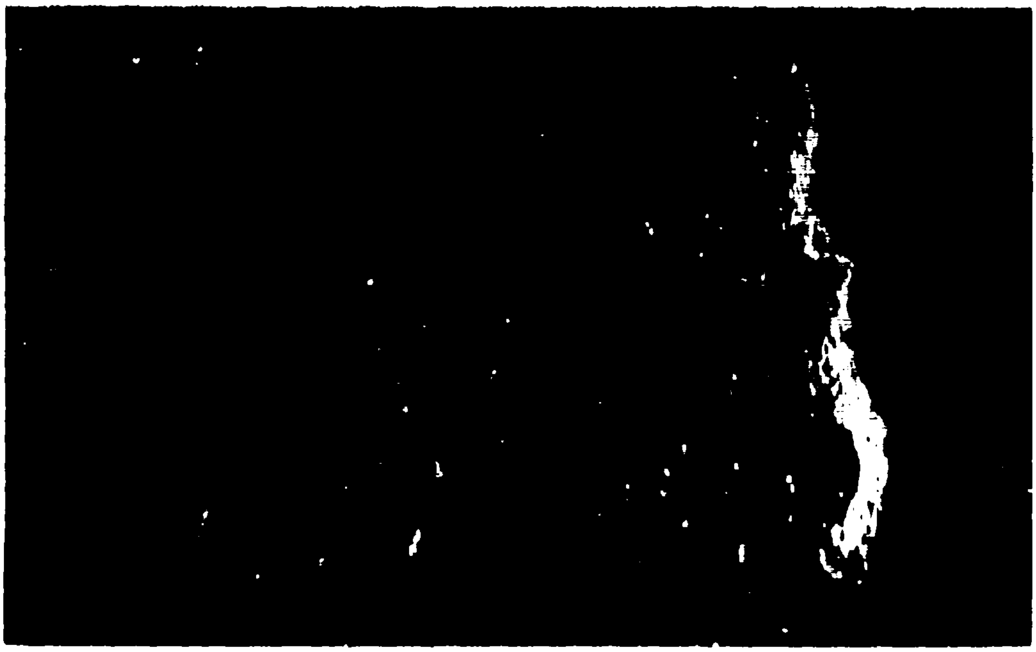

Figure 61 Control Specimen F-20 (no weld). Failed During 61st Cycle. Note Extensive Stress-Rupture Cracking. (Environmental-test conditions: 1800F, 3 ksi, salt; scheduled duration: 63 cycles) (H-68837) Mag: 15X

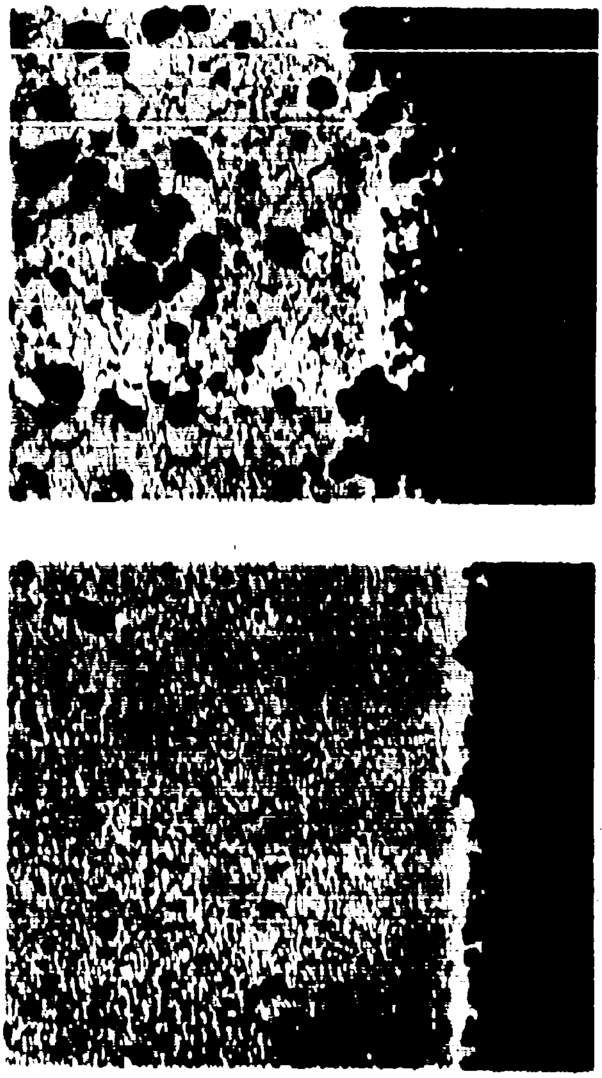

Figure 62 Photomicrographs of Welded Specimens F-2 (top) and F-9 (bottom). Specimen F-2 Failed During 58th Cycle, F-9 Completed 63 Cycles. Note More Extensive Cracking in Specimen F-2. (Environmental-test conditions: 1600F, 8 ksi, F-2 with salt, F-9 without salt; scheduled duration: 63 cycles) (EM-2398-5) (EM-2393-8)

Etchant: 10 HNO_3 + 10 HAC + 15 HCL + 65 H_2O Mag: 50X

Figure 63 Welded Specimen F-1 After Tensile Test. Fracture Occurred Outside the Weld Region (bracketed). (Environmental-test conditions: 1800F, 3 ksi, salt; duration: 63 cycles) (K-64080)

Mag: 7X

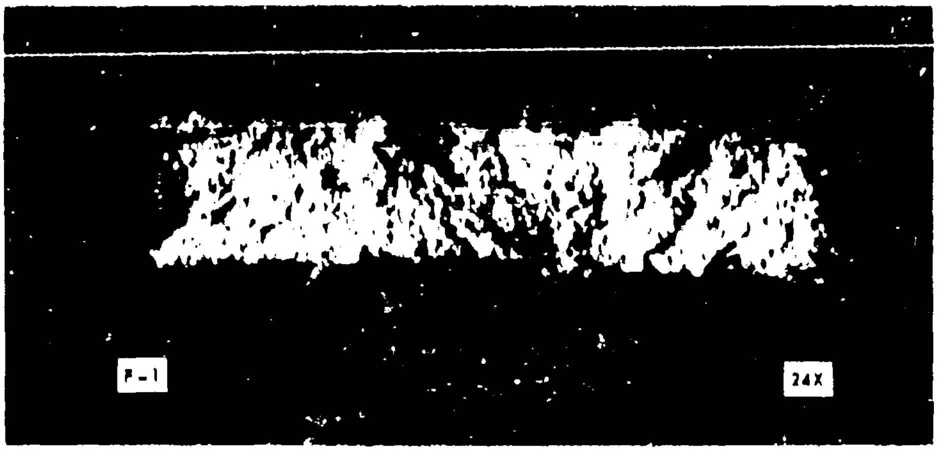

Figure 64 Welded Specimen F-1. Discoloration on Periphery of Fracture Surface. (Environmental-test conditions: 1800F, 3 ksi, salt; duration: 63 cycles) (H-64101, Mag: 24X

Rene 41 (Brazed) - All salted specimens of this group suffered corrosion of one form or another. Two instances of Type-(1) corrosion were detected. Both samples were exposed at 1800F; one at 3 ksi for 63 cycles (F-22), the other at 4 ksi for 19 cycles (F-26). Photographs of the discolored regions are shown in Figures 65 and 66. Tensile failures were located within the braze of specimen F-22 (Figure 67) and out of the braze but within the salt patch of F-26 (Figure 68). Extensive surface cracking and intergranular corrosion (maximum depth 0.024 inch) was evident along the entire gage length of both brazed and nonbrazed (control specimen F-40) salted specimens exposed at 1800F. Thus, this corrosion was not restricted to the small region to which the salt had been applied. The two unsalted specimens exposed at 1800F (F-37 and F-43), although showing signs of oxidation, experienced little intergranular cracking (maximum depth 0.003 inch). Representative photomicrographs showing these effects are presented in Figure 69. The two salted samples tested at 1500F and 4 ksi for 10 cycles (F-25 and F-26) were cracked somewhat less severely (maximum depth 0.012 inch) than salted material tested at 1800F and 3 ksi for 63 cycles (F-21 and F-22). Post-exposure tensile data in Table XXII also substantiate this observation. Comparing the tensile data for salted and unsalted specimens exposed at 1800F to those for brazed but unexposed material (F-34 and F-35), it is readily apparent that a gross deterioration of tensile strength and ductility occurred. This is not surprising, since, as was noted with welded specimens of this alloy, at 1800F René 41 rapidly over-ages. However, the deteriorating effects of the synthetic sea salt at this temperature are also readily apparent from the tensile data, the longer-time-exposure specimens degrading the most. These data also reveal that the unbrazed, salted, control specimen (F-40) exposed for 63 cycles deteriorated to the same degree as its brazed and salted counterparts (F-21 and

F-22, indicating that the presence of braze material had no apparent effect on the corrosion mechanism.

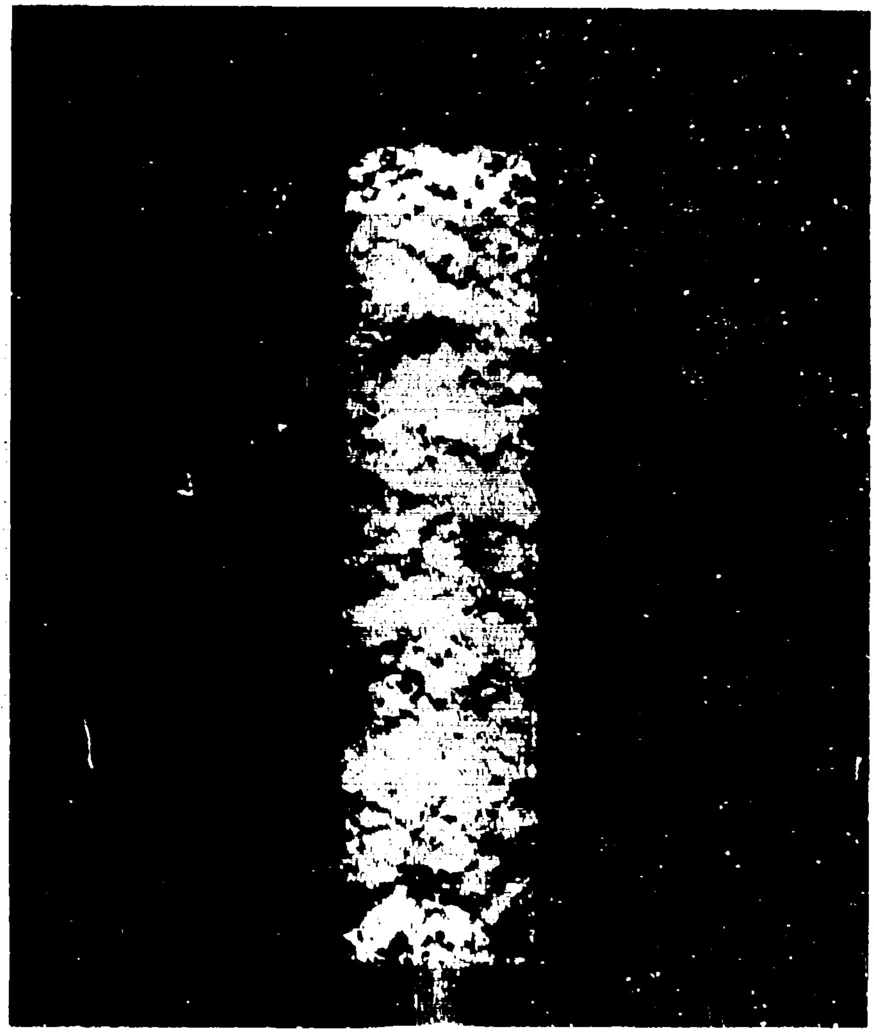

Figure 65 Brazed Specimen F-22 After Tensile Test. Arrow Points to Discoloration on Fracture Surface. (Environmental-test conditions: 1800F, 3 ksi, salt; duration: 63 cycles) (H-70308) Mag: 20X

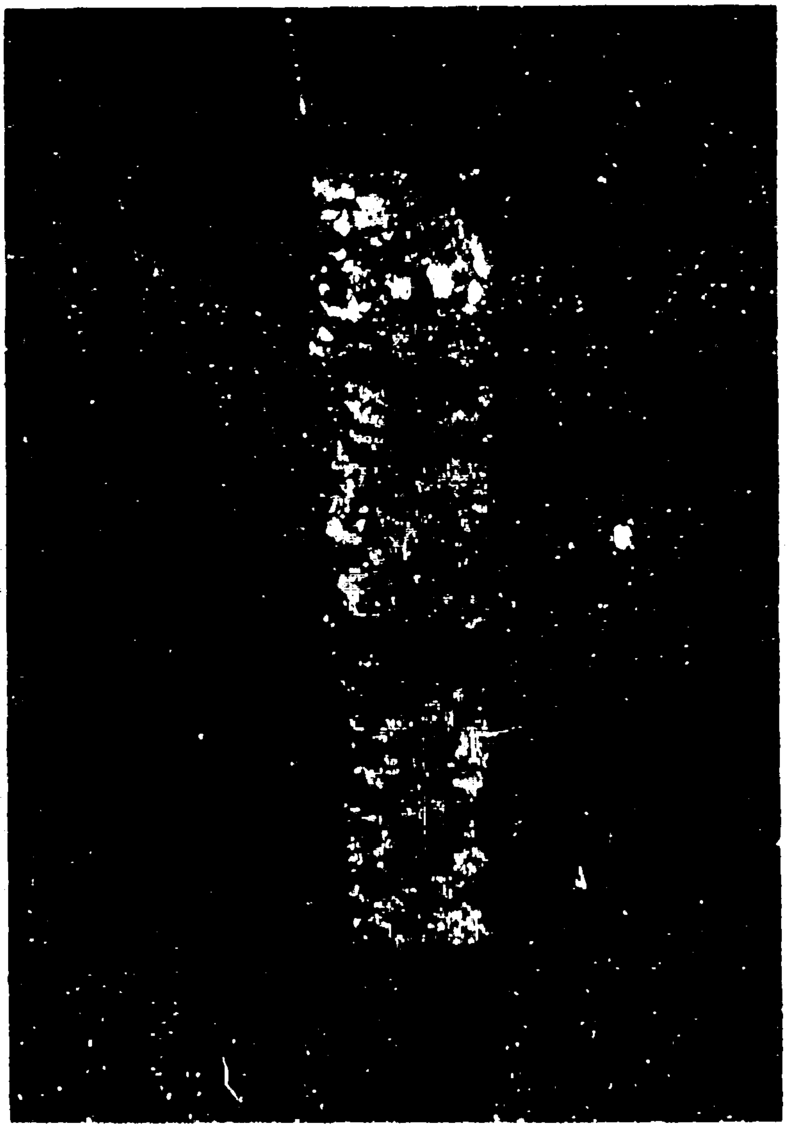

Figure 68 Brazed Specimen F-26 After Tensile Test. Arrow Points to Discoloration on Fracture Surface. (Environmental-test conditions: 1800F, 4 ksi, salt; duration: 19 cycles) (N-70371)
Mag: 20X

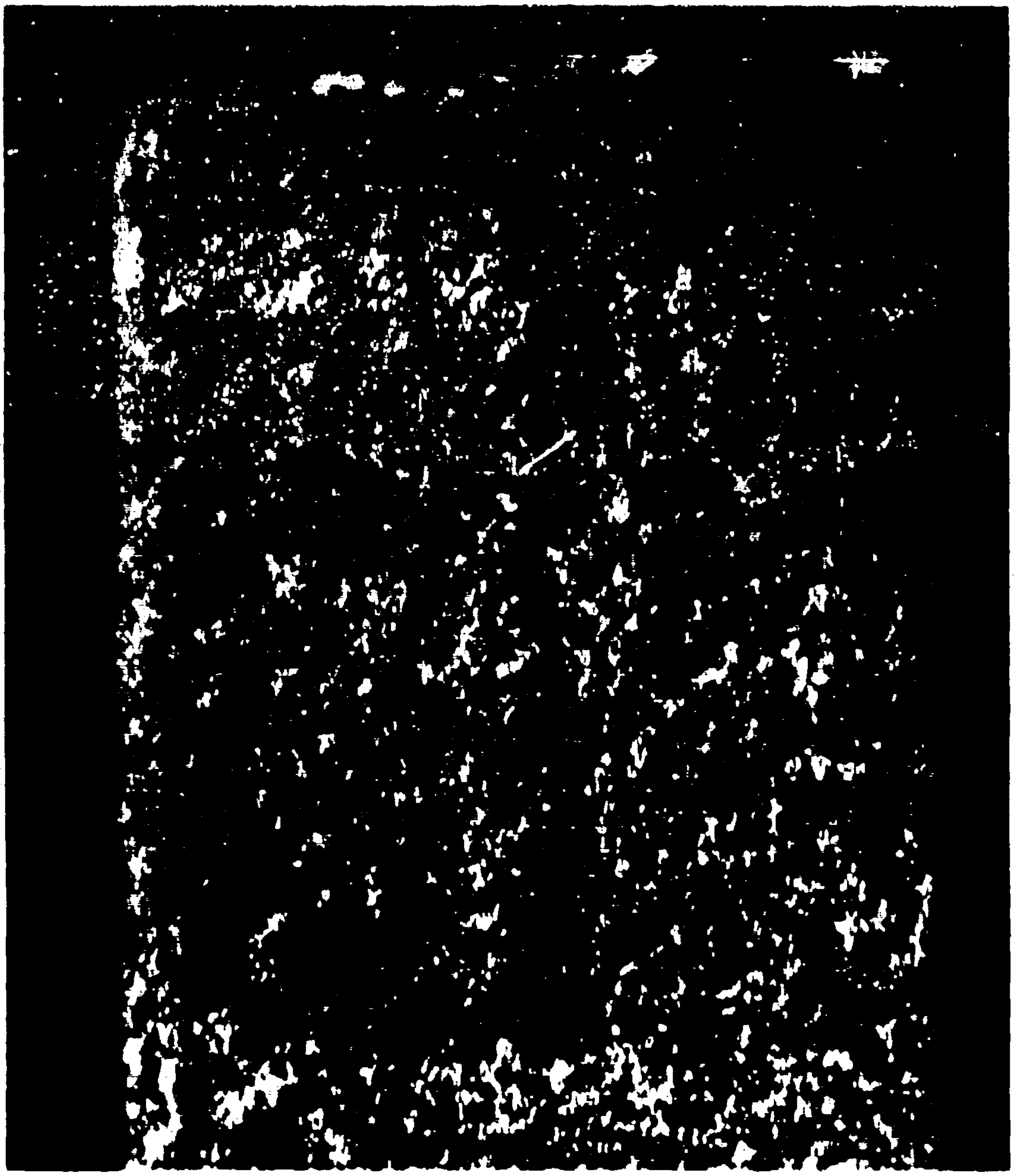

Figure 67 Brazed Specimen F-22 After Tensile Test, Showing Location of Rupture. (Environmental-test conditions: 1800F, 3 ksi, salt; duration: 63 cycles) (KP-2172-7)
Mag: 20X

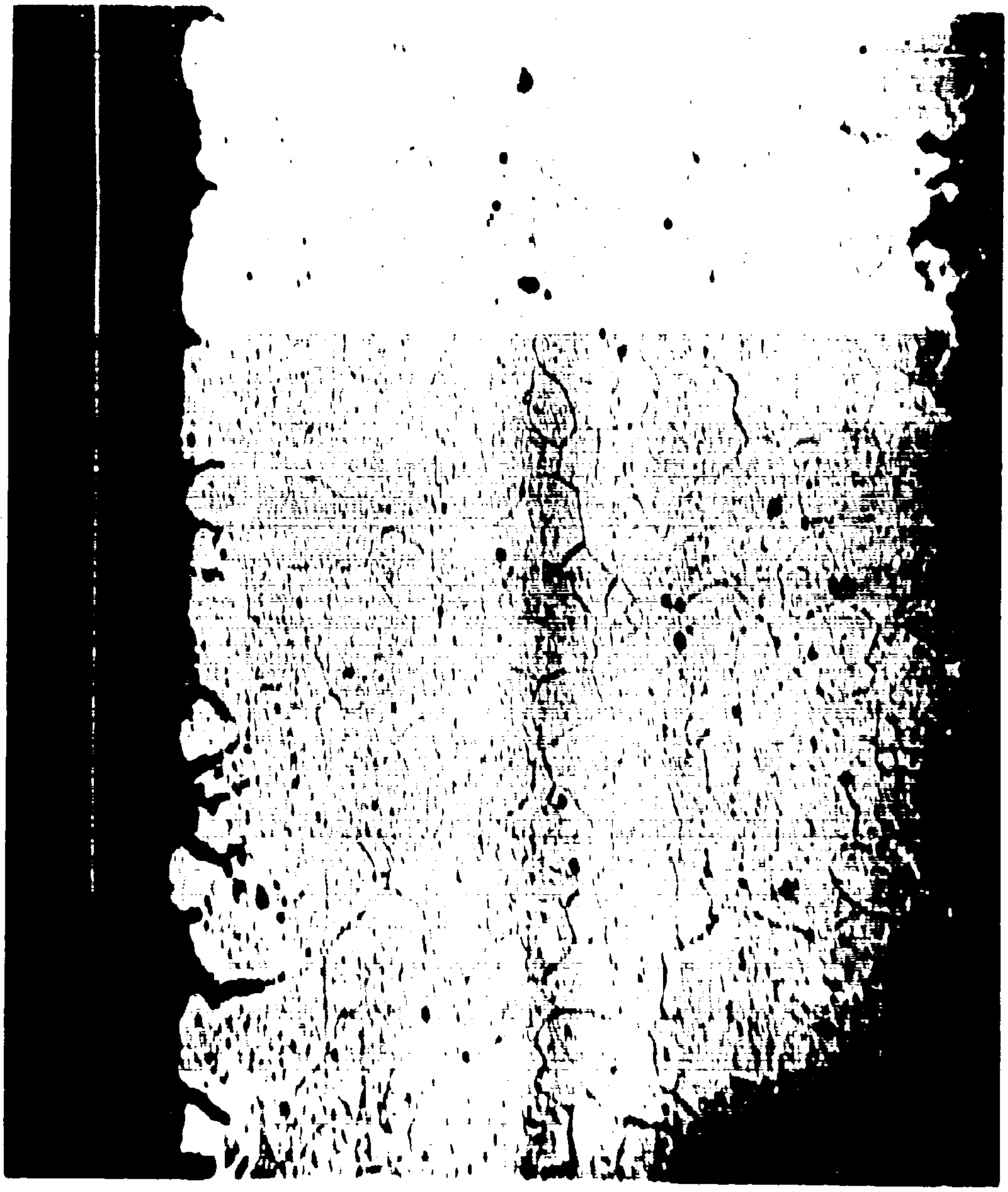

Figure 68 Photomicrograph of Brazed Specimen F-26 After Tensile Test, Showing Location of Rupture. (Environmental-test conditions: 1800F, 4 ksi, salt; duration: 10 cycles) (KP-2219-10)

Etchant: 10 HNO_3 + 10 HAC + 15 HCL + 65 H_2O Mag: 82X

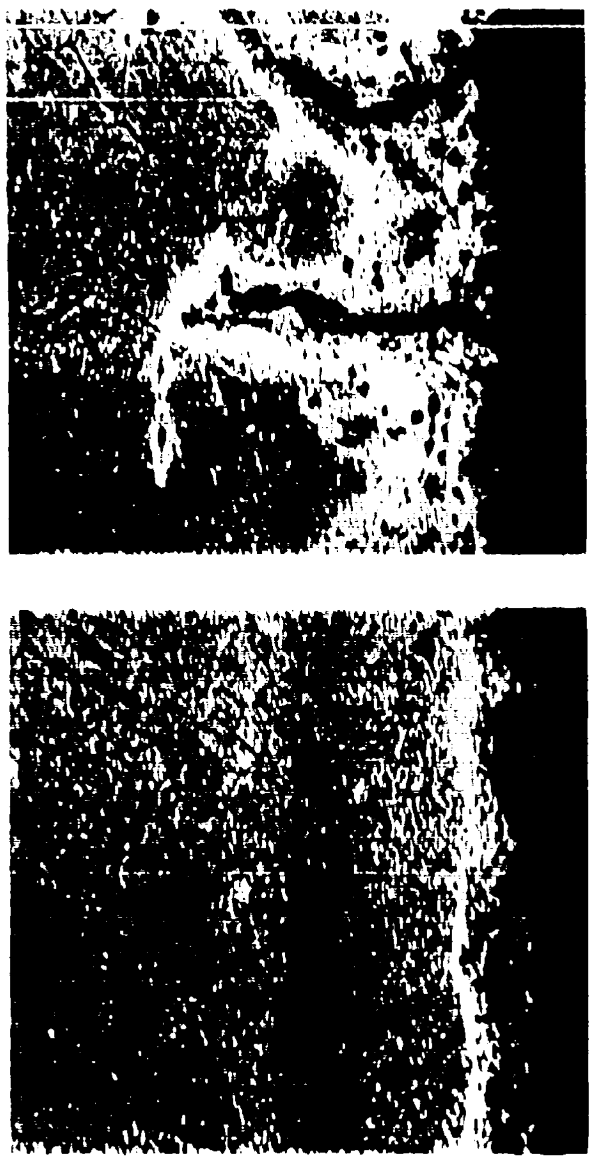

Figure 60 Brazed Specimens F-22 (top) and F-37 (bottom). Photomicrographs of Sections Adjacent to Fracture Surfaces. (Environmental-test conditions: 600F, 3 ksi, F-22 with salt, F-37 without salt; duration: 63 cycles) (KP-1004-1)(KP-1004-2)

Etchant: 10 HNO_3 + 10 HAC + 15 HCL + 65 H_2O Mag: 250X

Although none of the samples exposed at 1600F showed evidence of localized discolorations on their fracture surfaces, a corrosive mechanism was certainly in operation at this temperature. This mechanism was markedly different from that observed at 1800F. Two of the salted samples exposed at 1600F (F-23 and F-24) failed during environmental exposure. Examination of the specimens revealed that the gage thickness at the braze-to-parent-metal interface was reduced by approximately 55% (Figure 70), thus resulting in a stress-rupture failure. The same type of deterioration (thickness reduced 47%) was observed in the two samples exposed at 1600F and 17 ksi for 19 cycles (F-27 and F-28), but the shorter times involved did not allow stress rupture to occur. This phenomenon was not operative in the unsalted samples, nor was it found in salted, René-41 welded specimens exposed under identical conditions. Therefore, at 1600F salt produced severe galvanic corrosion in brazed specimens. As shown in Table XXII, the unsalted specimens exposed at 1600F and 13 ksi for 63 cycles experienced a loss in tensile strength and ductility due to the temperature exposure only. Thus, as was experienced with the welded samples of this material, 1600-F exposure also resulted in over-aging of the alloy.

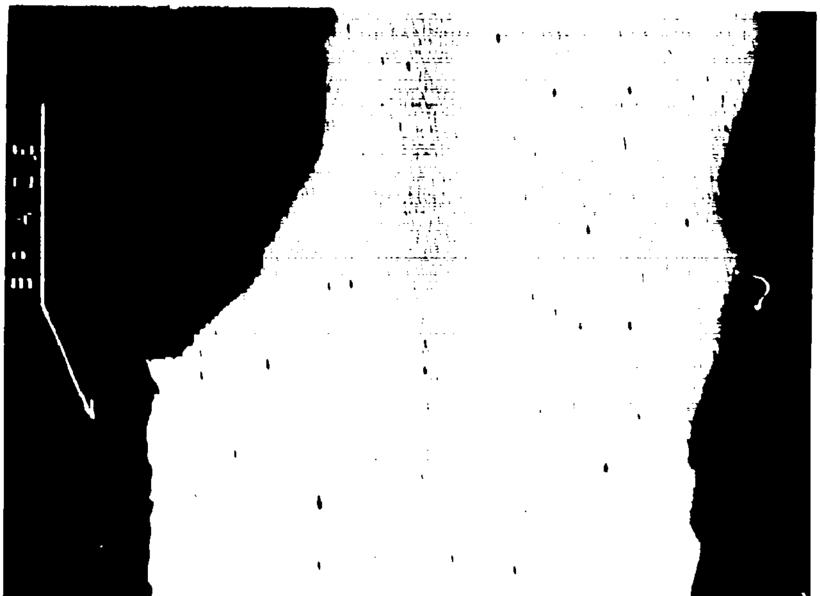

Figure 70 Brazed Specimen F-24. Failed During 42nd Cycle. Note Gross Reduction in Gage Section Adjacent to Braze. (Environmental-test conditions: 1600F, 13 ksi, salt; scheduled duration: 63 cycles)

(KP-2001-1)

Etchant: 10 HNO_3 + 10 HAC + 15 HCl + 65 H_2O Mag: 88X

In summary of the results discussed above, it was observed that, at 1800F, salted specimens, both brazed and unbrazed, suffered extensive intergranular corrosion and cracking, with resultant loss in tensile properties. Two instances of Type-(1) corrosion were found at this temperature. At 1600F, although no evidence of Type-(1) or Type-(3) corrosion was found, the brazed and salted specimens suffered severe galvanic corrosion. This type of corrosion was not evident at 1600F in the welded specimens, since the weld filler material was parent metal. Tables XXII and XV indicate that brazing has no effect on strength after exposure.

Udimet 700 (Welded) - Tables XXIII and XV summarize the test history for this material. None of the welded specimens experienced salt corrosion, although all of those tested at 1900F and one of those tested at 1600F failed before completion of scheduled cyclic exposure. All failures were of the brittle type. The results of the post-exposure, room-temperature, tensile tests of the five specimens which completed their scheduled number of cycles and the measured hardness values of all specimens indicated that the material had been over-aged by the exposure. Macrophotographs of typical failed specimens, salted and unsalted, are shown in Figures 71, 72, and 73. Based on microexaminations, it could not be said that salted specimens were cracked more severely than unsalted material (Figure 74).

One welded U-700 specimen (G-8) showed evidence of sulfidation in the form of a light-gray globular phase. The arrow in Figure 75 points to sulfide particles in a cross section through the salted region. The extent of sulfidation was quite limited. Analysis by electron microscopy verified that the phase was chrome-rich sulfide. The specimen had survived its scheduled exposure of 63 cycles at 1600F. No cracks associated with the sulfidation were found on metallographic examination of the specimen.

This instance of sulfidation was confined to the one welded U-700 specimen; there was no evidence of sulfidation found in any of the specimens of the other nine materials investigated in the program.

Udimet 700 (Brazed) - Brazed specimens experienced a degradation in overall capability at 1900F similar to that found in the welded specimens. The salted (G-21 and G-22) and unsalted (G-20 and G-37) specimens which were exposed at 1900F and 3.0 ksi failed before completing the scheduled 63 cycles. Microexamination revealed cracking to be more extensive in the two salted specimens (Figure 76). The two salted specimens (G-35 and G-38) also tested at 1900F but at 5.0 ksi, survived their scheduled 19 cycles. It was apparent from the testing of both welded and brazed specimens that, at the maximum exposure temperature and time, the material would fail in stress rupture before the presence of salt could be of significance.

TABLE XXIII

ENVIRONMENTAL-TEST HISTORY: UDIMET-700 ALLOY SPECIMENS

		Exposure Conditions					Post-Exposure Room-Temperature Tensile Properties						Post-Exposure Hardness
Specimen No.	Joint Type	Salt	Temp (F)	Stress (ksi)	Cycles Sched.	Cycles Compl'd	UTS (ksi)	0.2% YS (ksi)	El (%)	Failure Mode	Failure Loc.[1]	Salt Corrosion[2]	Rockwell C
G-1	Weld	Yes	1900	3	63	47.3	-	-	-	Granular	3	No	32
G-15	Weld	Yes	1900	3	63	50.2	-	-	-	Granular	1	No	34
G-3	Weld	Yes	1600	24	63	63	157	117	10	Granular	1	No[3]	[illegible]
G-4	Weld	Yes	1600	24	63	41.8	-	-	-	20% Shear	2	No	39
G-9	Weld	No	1900	3	63	32.2	-	-	-	Granular	4	-	34
G-10	Weld	No	1900	3	63	46.6	-	-	-	Granular	4	-	34
G-13	Weld	No	1600	24	63	63	163	124	10	Granular	1	-	38
[illegible]	Weld	Yes	1600	29	19	19	176	125	12	Granular	1	No	39
G-8	Weld	Yes	1600	29	19	19	175	128	14	Granular	1	No	40
G-5	Weld	Yes	1900	6	19	10	-	-	-	Granular	3	No	36
G-6	Weld	Yes	1900	5	19	14.2	-	-	-	Granular	3	No	32
G-11	Weld	-	-	-	-	-	199	155	11	Granular	1	-	43
G-12	Weld	-	-	-	-	-	204	155	14	Granular	1	-	44
G-19	None	No	1900	3	63	54.	-	-	-	Granular	-	-	37
G-20	None	Yes	1900	3	63	52.3	-	-	-	Granular	5	No	30
G-21	Braze	Yes	1900	3	63	43.	-	-	-	Granular	2	No	33
G-22	Braze	Yes	1900	3	63	47.	-	-	-	Granular	3	No	32
G-23	Braze	Yes	1600	24	63	63	122	101	7	Granular	2	No	35
G-24	Braze	Yes	1600	24	63	63	105	99	4	Granular	2	No	34
G-29	Braze	No	1900	3	63	38.9	-	-	-	Granular	4	-	34
G-37	Braze	No	1900	3	63	44.9	-	-	-	Granular	4	-	33
G-32	Braze	No	1600	24	[illegible]	63	145	104	12	Granular	4	-	33
[illegible]	Braze	No	1600	24	63	63	153	105	15	Granular	1	-	36
G-27	Braze	Yes	1600	29	19	19	139	113	9	Granular	2	No	34
G-28	Braze	Yes	1600	29	19	19	132	109	8	Granular	2	No	35
G-25	Braze	Yes	1900	5	19	19	133	104	16	Granular	2	No	34
G-26	Braze	Yes	1900	5	19	19	109	104	3	Granular	2	No	36
G-30	Braze	-	-	-	-	-	105	125	17	Granular	1	-	40
G-31	Braze	-	-	-	-	-	186	136	17	Granular	4	-	41
G-39	None	No	1900	3	63	63	102	94	4	Granular	-	-	31
G-40	None	Yes	1900	3	63	23	-	-	-	Granular	5	No	29

Notes: (1) Failure-location identification
1. Through joint
2. Away from joint but through salt
3. Away from salt
4. Away from joint (no salt on specimen)
5. Through salt (no joint)

(2) Salt corrosion of Types 1 and/or 3, as identified in text
(3) Sulfidation evident

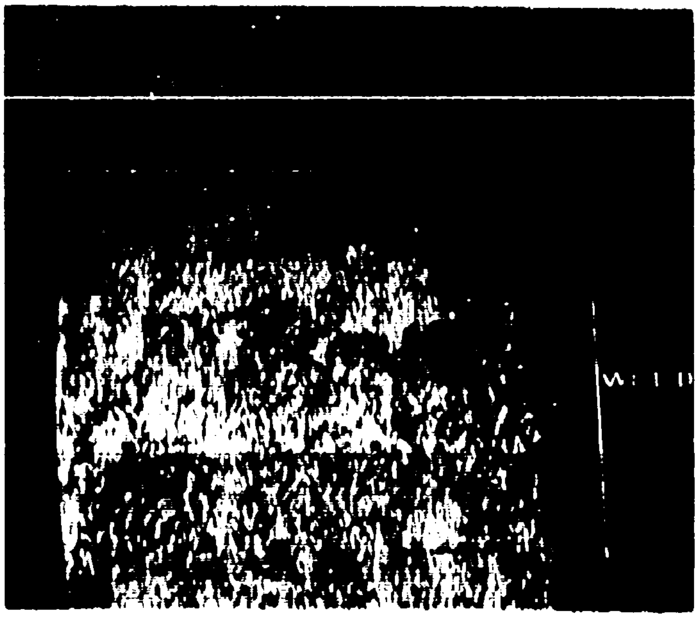

Figure 71 Welded Specimen C-15. Failed During 51st Cycle. (Environmental-test conditions: 1000F, 3 ksi, salt; scheduled duration: 65 cycles)
(EP-2172-6)
Mag: 6X

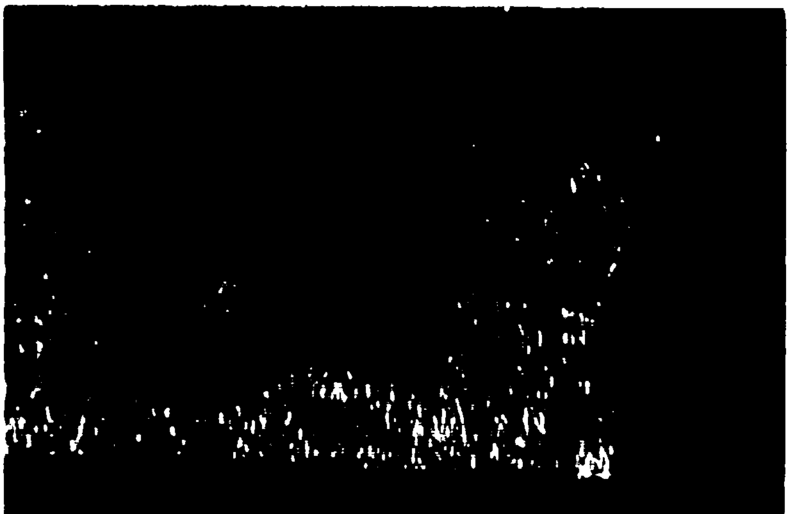

Figure 72 Welded Specimen C-8. Failed During 15th Cycle. (Environmental-test conditions: 1000F, 5 ksi, salt; scheduled duration: 19 cycles)
(11-08848)
Mag: 11X

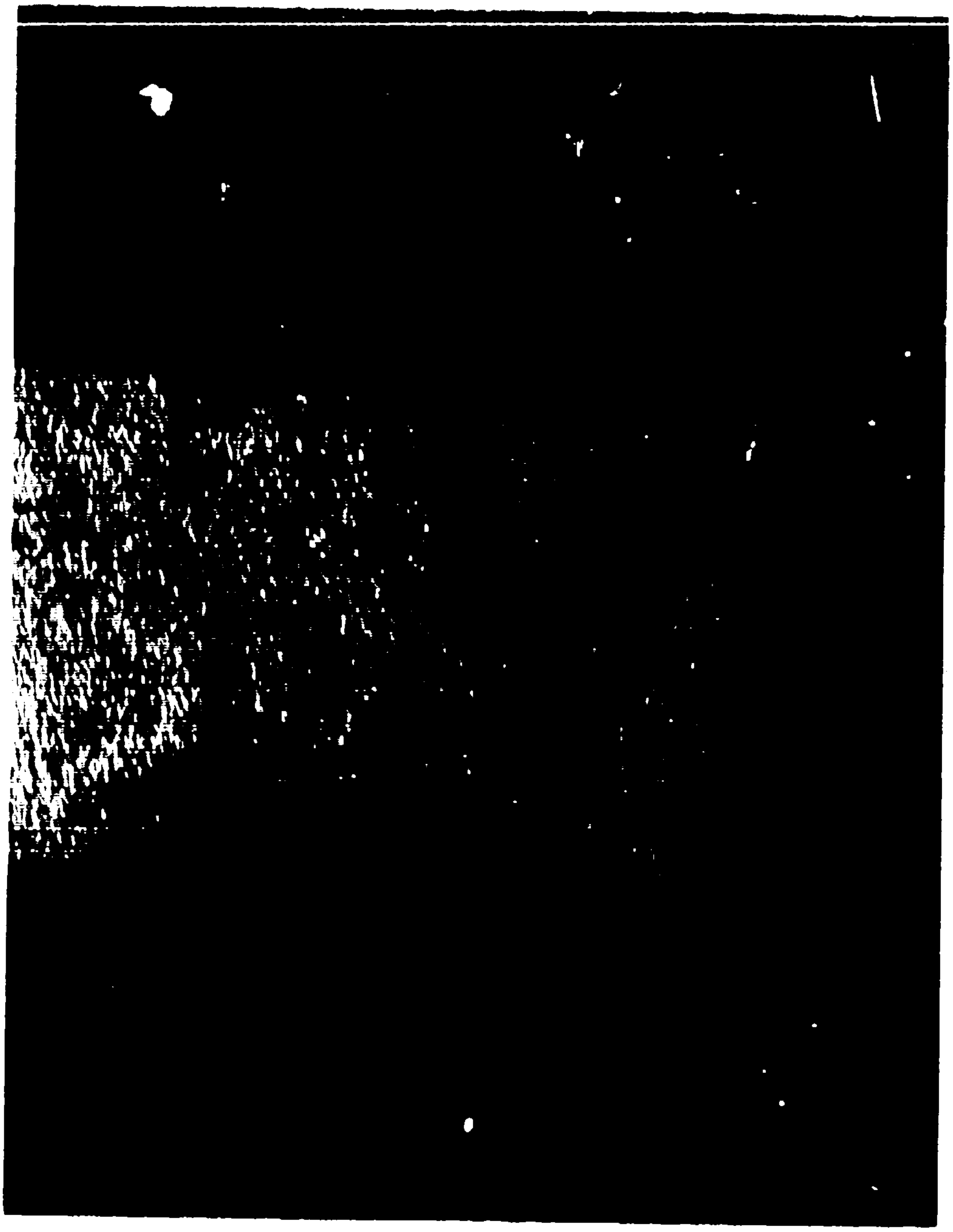

Figure 73 Welded Specimen G-9, Failed During 33rd Cycle. (Environmental-test conditions: 1000F, 3 ksi, no salt; scheduled duration: 63 Cycles)

(J-63844) Mag: 15X

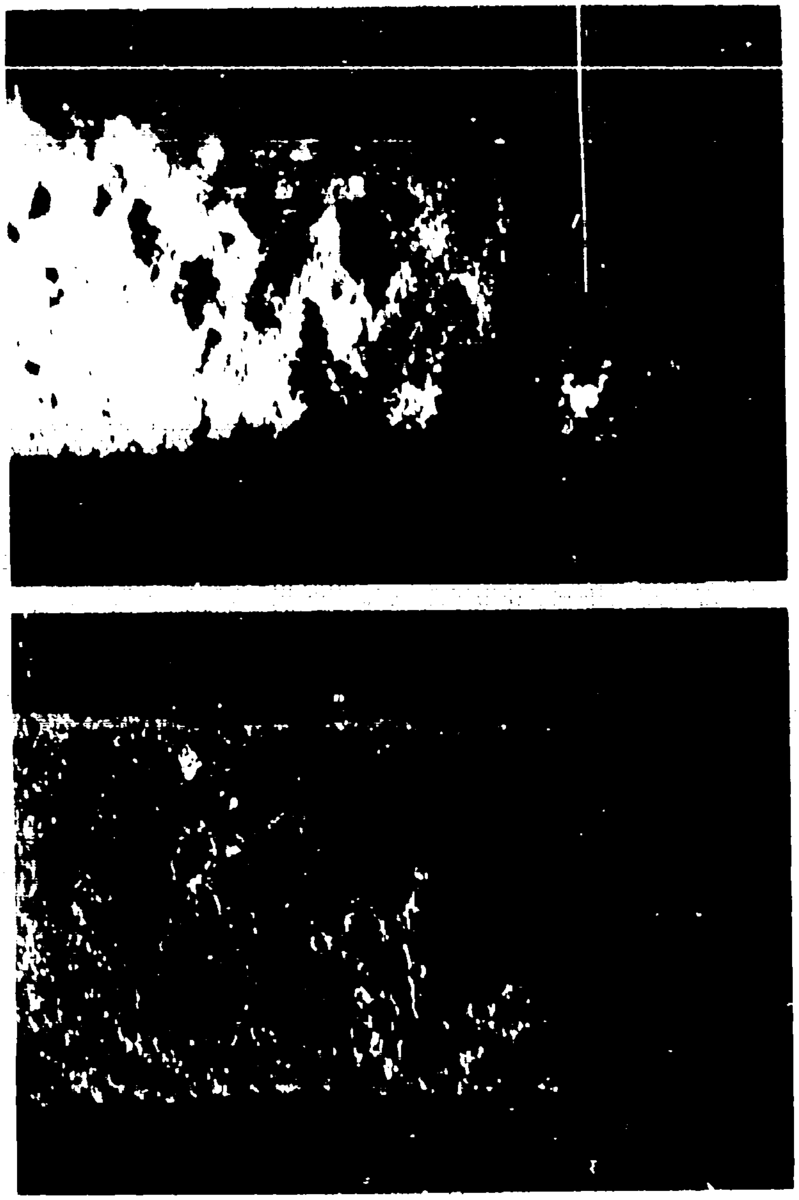

Figure 74 Photomicrographs of Welded Specimens G-1 (top) and G-9 (bottom). Specimen G-1 Failed in 48th Cycle, G-9 in the 33rd Cycle. (Environmental-test conditions: 1900F, 3 ksi, G-1 with salt, G-9 without salt; scheduled duration: 63 cycles) (EP-2233-4)(EP-2233-5)

Etchant: 10 HNO_3 + 10 HAC + 15 HCL + 65 H_2O Mag: 50X

Figure 75 Welded Specimen G-3. Photomicrograph Showing Sulfide Particles (arrow) in Cross-Section Through Salt Region. (Environmental-test conditions: 1600F, 24 ksi, salt; duration: 63 cycles)

(EM-0390A-1)

Etchant: 10 HNO_3 + 10 HAC + 15 HCl + 65 H_2O Mag: 1000X

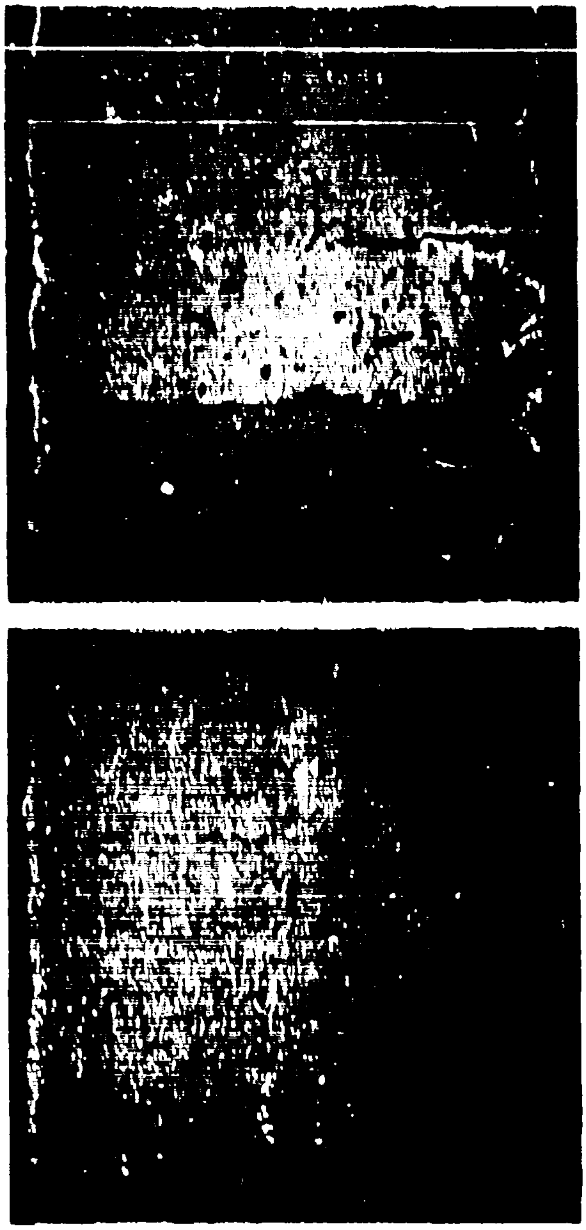

Figure 76 Photomicrograph of Brazed Specimens G-21 (top) and G-37 (bottom). Specimen G-21 Failed in 43rd Cycle, G-37 in 45th Cycle. (Environmental-test conditions: 1000F, 5 ksi, G-21 with salt, G-37 without salt; scheduled duration: 63 cycles) (KP-2250-5) (KP-2250-6)

Etchant: 10 HNO_3 + 10 HAC + 15 HCL + 65 H_2O Mag: 45X

All four brazed and salted specimens exposed at 1600F survived their scheduled number of cycles and exhibited lower ultimate-tensile strength and ductility than the unsalted 1600F-exposure specimens. The lower strength was attributed to the more extensive cracking (not Type-(1) or Type-(3) corrosion) which occurred in the salted specimen (Figure 77). As was true for those which had been tested at 1900F, the 1600-F-exposure specimens evidenced over-aging (note drop in hardness values given in Table XXIII). As Table XV indicates, corrosion, cycling, and temperature all degrade the strength of brazed Udimet 700.

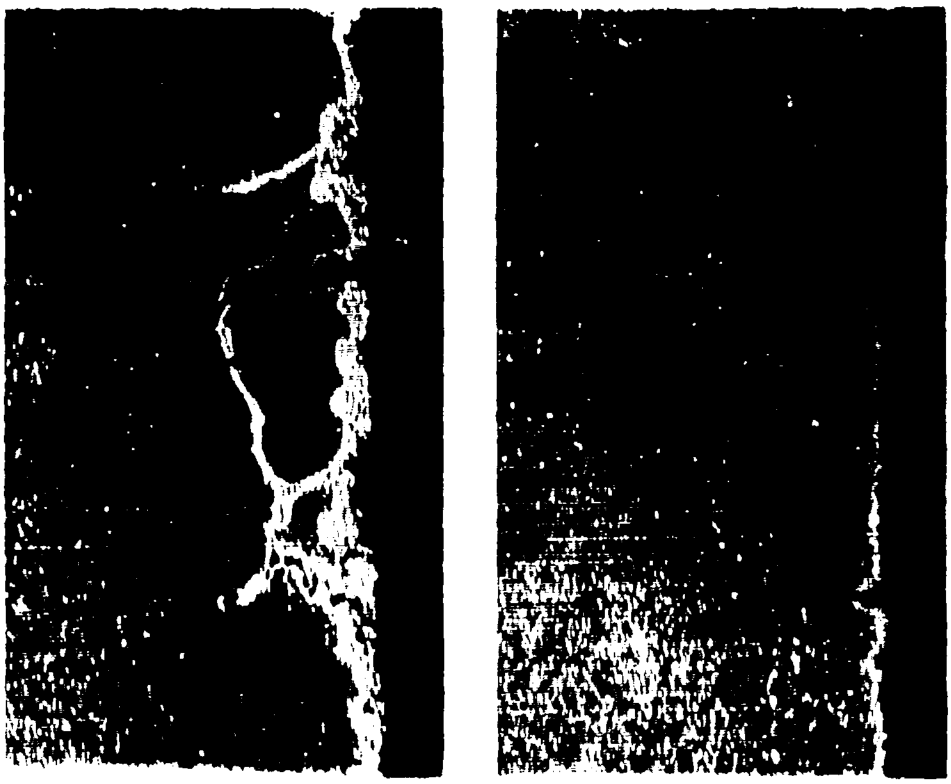

Figure 77 Photomicrographs of Brazed Specimens G-33 (left) and G-32 (right) After Tensile Test. (Environmental-test conditions: 1600F, 24 ksi, (G-33 with salt, G-32 without salt; duration: 63 cycles) (EP-2230-9)
(EP-2230-8)

Etchant: 10 HNO_3 + 10 HAC + 15 HCL + 65 H_2O Mag: 250X

A 286 (Welded) - The test history for specimens of this material appears in Table XXIV. No evidence of Type-(1) or Type-(3) corrosion was discovered following environmental testing. Furthermore, there were no failures encountered in the course of such testing. All specimens exposed at 1200F exhibited an increase in tensile strength compared to the tensile strengths of unexposed material (H-11 and H-12). This was due presumably to additional aging. A trend toward increased hardness values was also apparent. The two salted specimens (H-1 and H-2) exposed at 1200F and 30 ksi showed somewhat lower tensile strengths than their unsalted counterparts (H-13 and H-15), although no significant cracking could be attributed to the applied salt (Figure 78). All four specimens failed through the welds or subsequent tensile testing (Figure 79). Salted specimens evaluated at 800F for 63 and 19 cycles had essentially the same tensile properties as unsalted specimens tested at 800F for 63 cycles, and also as unexposed material. Thus, at the lower temperature, salt had no apparent effect on the tensile properties of the alloy. Tables XXIV and XV indicate welding reduces strength after exposure.

TABLE XXIV

ENVIRONMENTAL-TEST HISTORY: A-286 ALLOY SPECIMENS

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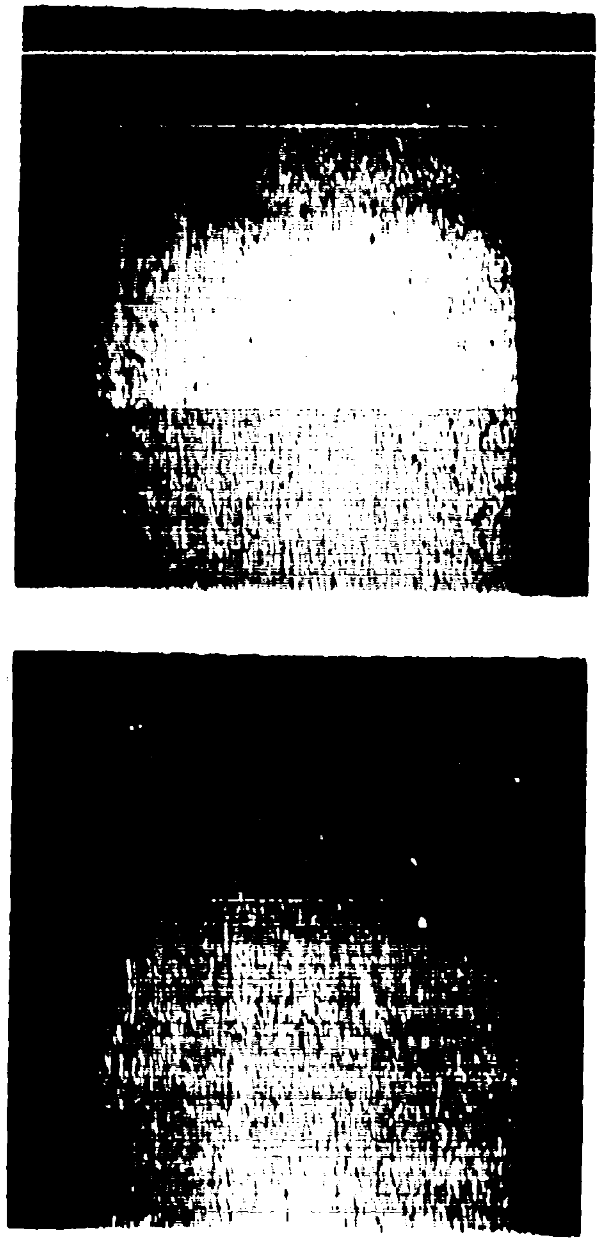

Figure 78 Photomicrographs of Welded Specimens H-2 (top) and H-13 (bottom) After Tensile Test. (Environmental exposure: 1200F, 30 ksi, H-2 with salt, H-13 without salt; duration: 63 cycles) (EP-2230-1) (EP-2230-2)

Etchant: HCL/CH_3OH Mag: 50X

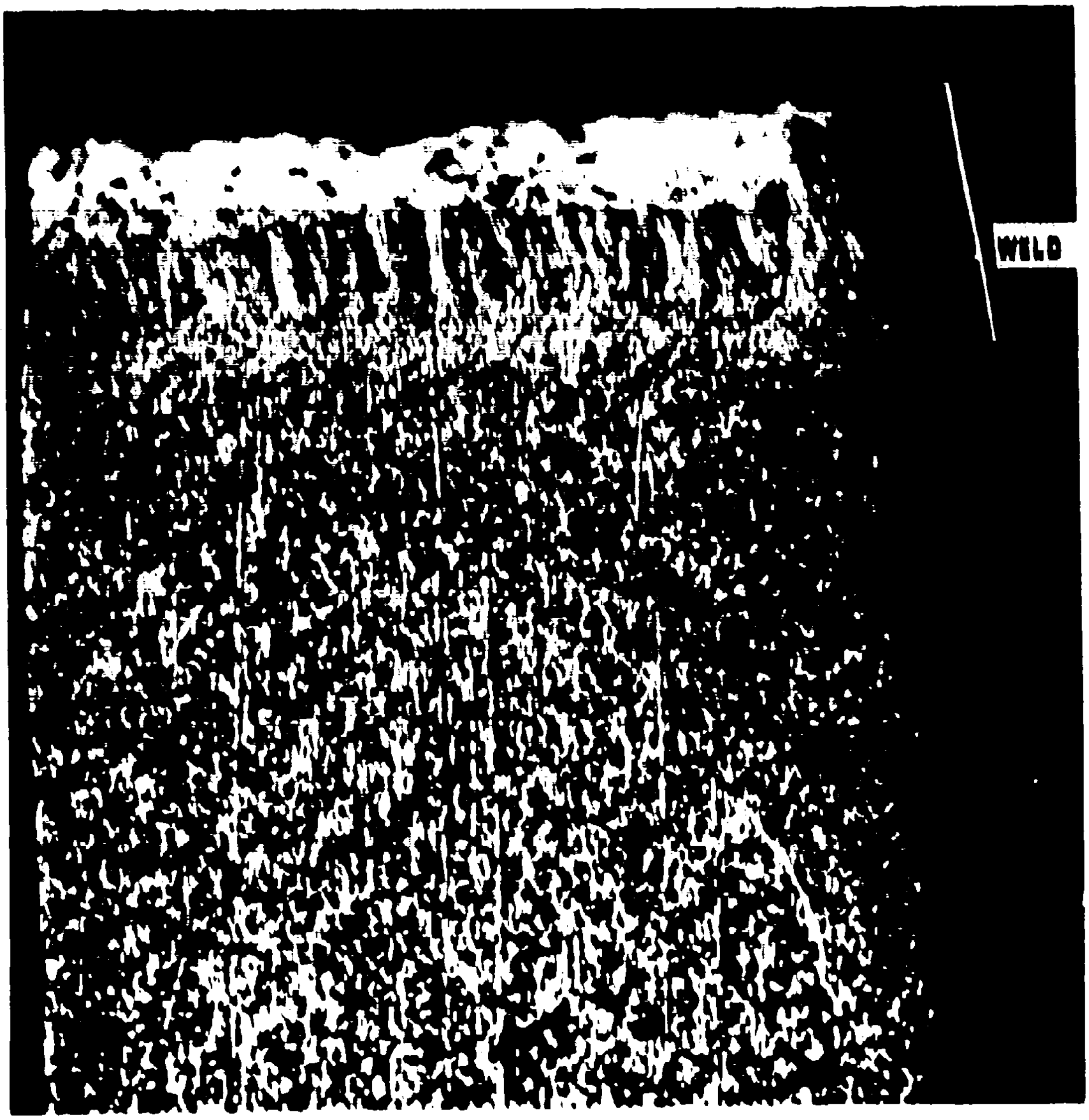

Figure 76 Welded Specimen II-8 After Tensile Test, Showing Rupture Location. (Environmental-test conditions: 1200F, 30 ksi, salt; duration 63 cycles)
(EP-2172-3)
Mag: 20X

A 286 (Brazed) - The brazed specimens of this alloy exposed at 800F performed as did their welded counterparts; that is, strengths and ductilities of salted, unsalted, 19- and 63-cycle specimens were essentially identical to the values of those properties measured on unexposed material (H-26 and H-27). In addition, the two unsalted, brazed specimens (H-38 and H-43) evaluated at 1200F and 30 ksi for 63 cycles and the two salted specimens (H-32 and H-34) tested at 1200F and 35 ksi for 19 cycles showed an increase in tensile strength and hardness (Table XXIV). Thus, additional aging occurred during environmental exposure. However, the two brazed and salted specimens (H-23 and H-24) exposed at 1200F and 30 ksi for 63 cycles experienced a decrease in strength and ductility as compared to their unsalted counterparts. Although no evidence of Type-(1) or Type-(3) corrosion was found on the fracture surfaces of the lower-strength samples (or any other samples of this group), a significant amount of surface cracking was evident subsequent to tensile testing, as shown in Figure 80. The majority of the ruptures occurred outside of the brazed area (Figure 81). As Tables XXIV and XV indicate, cycling at both high and low temperature and salt at high temperature reduce the strength after exposure.

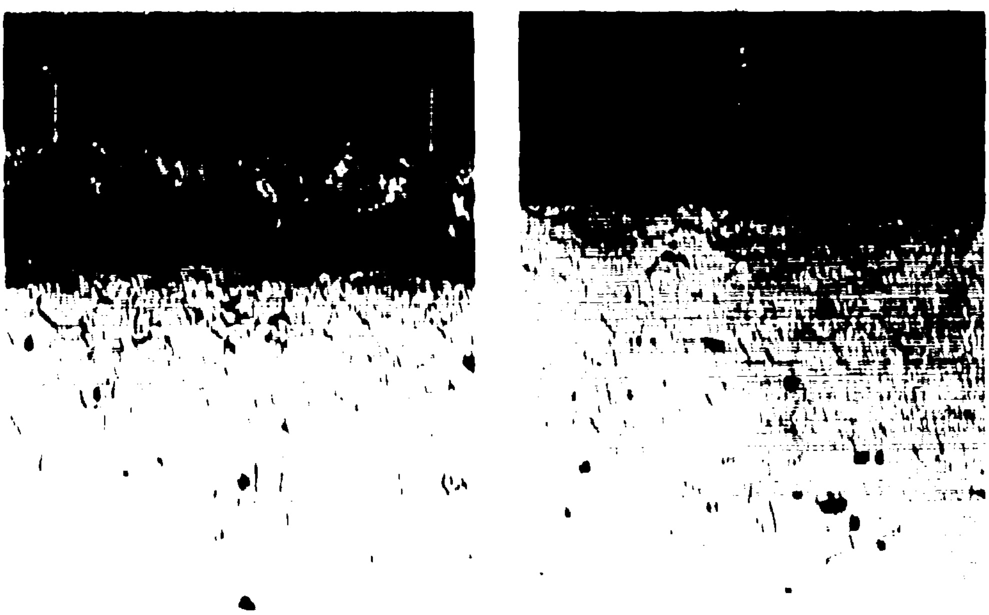

Figure 80 Photomicrographs of Brazed A-286 Specimens After Tensile Test. Note Severe Cracks (arrows) in Salted, Brazed Area of Sample H-24 (left) and Sound Braze in Unsalted Sample H-38 (right). (Environmental-test conditions: 1200F, 30 ksi; duration: 63 cycles)

(EP-1887-8) (EP-1887-7)

Etchant: ACIDIC $FeCl_3$ Mag: 250X

Figure 61 Brazed Specimen H-84 After Tensile Test, Showing Location of Rupture. (Environmental-test conditions: 1900F, 35 ksi, salt; duration: 10 cycles) (EP-2172-4)
Mag: 30X

TABLE XXV

ENVIRONMENTAL-TEST HISTORY: GREEK-ASCOLOY ALLOY SPECIMENS

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Greek Ascoloy (Welded and Brazed) - The test history of this material appears in Table XXV. No failures during cyclic testing and no indications of salt corrosion were encountered. Both groups of specimens exhibited increased yield strengths due to their elevated-temperature exposure, as compared to the yield strengths of unexposed specimens, and all ruptured out of the welded or brazed areas (Figures 82 and 83). However, Table XV indicates that corrosion, temperature, and cycling did not affect strength. No non-brazed control specimens are reported for this alloy because, after post-exposure tensile testing, it was revealed by a hardness check that these had not been tempered.

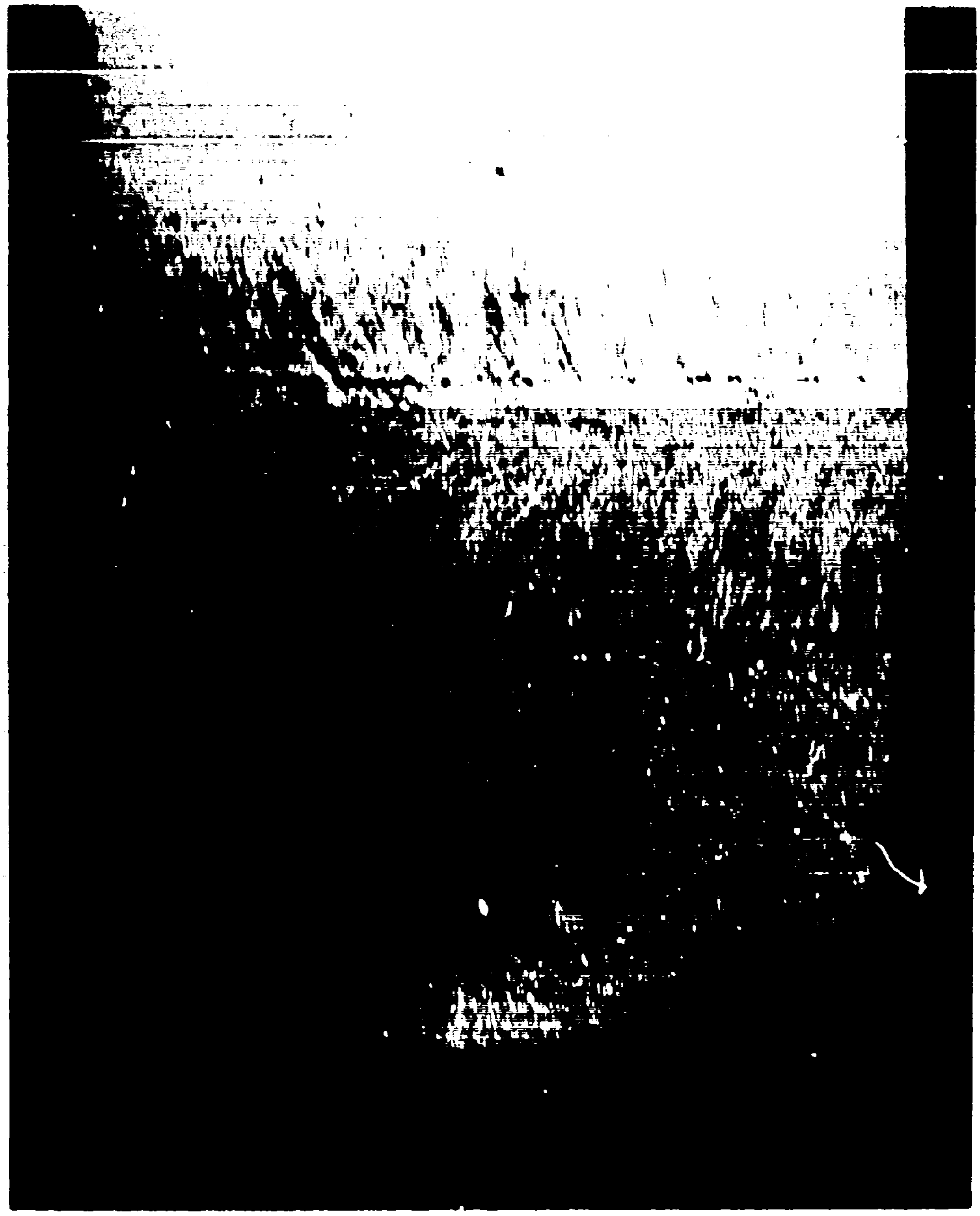

Figure 52 Welded Specimen I-6 After Tensile Test, Showing Rupture Location. (Environmental-test conditions: 800F, 55 ksi, salt; duration: 10 cycles)

(KP-8178-1)

Mag: 20X

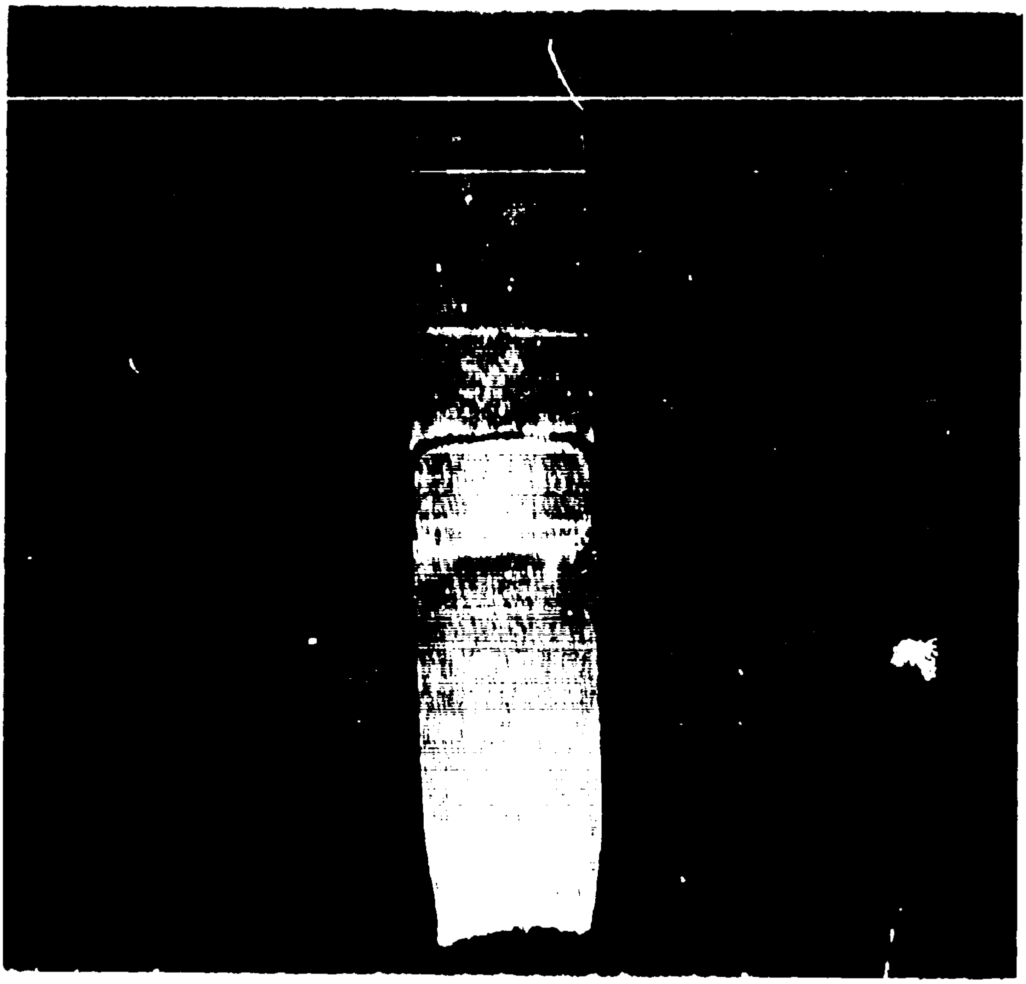

Figure 83 Brazed Specimen I-55 After Tensile-Test, Showing Location of Rupture. (Environmental-test conditions: 800F, 55 ksi, salt, duration: 10 cycles) (KP-2172-15) Mag: 4X

TD Nickel (Welded) - The test history for specimens of this material appears in Table XXVI. No instances of stress corrosion were observed. It will be noted that all four specimens tested at 1000F failed within two cycles and that, of the six tested at 2000F, three failed in less than ten cycles and three were removed from test after ten cycles because of excessive deterioration at the weld. All of the specimens which did not survive for ten cycles failed in the welded region. Figure 84 is a photograph showing the fracture surface of a typical failed specimen. Where failure occurred, separation was at the

Waspaloy - TD-nickel interface, as shown in Figure 85. The failures at the weld interfaces were not anticipated. When a tensile test was conducted at room temperature on an unexposed welded specimen, rupture occurred in the parent metal, thus demonstrating the integrity of the weld. Also, pre-test X-ray and sonic inspections had not detected any imperfections in the joints. However, several of the unexposed welded specimens, when examined metallographically, had been observed to have Waspaloy filler material in the "V" grooves of the welds, but very little of that material in the center portions, as can be seen in Figure 86. The combination of limited heat input, to avoid agglomeration of thoria, and the restriction on expansion imposed by the welding fixture which forced the parent-metal interfaces together during welding, prevented sufficient Waspaloy filler material from entering the root region. The specimens were welded using state-of-the-art techniques available at the time the work specified by the Contract was performed.

TABLE XXVI

ENVIRONMENTAL-TEST HISTORY: TD-NICKEL ALLOY SPECIMENS

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[illegible]	Weld	No	[illegible]	[illegible]	[illegible]	[illegible]	-	-	-	[illegible]	[illegible]	-	[illegible]
[illegible]	Weld	Yes	[illegible]	[illegible]	[illegible]	[illegible]	-	-	-	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Weld	Yes	[illegible]	[illegible]	[illegible]	[illegible]	-	-	-	[illegible]	[illegible]	[illegible]	[illegible]
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[illegible]	Weld	Yes	[illegible]	[illegible]	[illegible]	[illegible]	-	-	-	[illegible]	[illegible]	[illegible]	[illegible]
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[illegible]	[illegible]	No	[illegible]	[illegible]	[illegible]	[illegible]	-	-		[illegible]	[illegible]		[illegible]
[illegible]	[illegible]	No	[illegible]	[illegible]	[illegible]	[illegible]		-	-	[illegible]	[illegible]	-	[illegible]
[illegible]	[illegible]	No	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-	[illegible]
[illegible]	[illegible]	No	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]
[illegible]	[illegible]	Yes	[illegible]	[illegible]	[illegible]	[illegible]	-	-	-	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	Yes	[illegible]	[illegible]	[illegible]	[illegible]	-	-	-	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	Yes	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	Yes	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	-	-	-	-	-	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-	[illegible]
[illegible]	[illegible]	-	-		-	-	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-	[illegible]
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[illegible]	None	Yes	[illegible]	[illegible]	[illegible]	[illegible]	-	-	-	[illegible]	[illegible]	[illegible]	[illegible]

Notes: (1) [illegible]
1. Through [illegible]
2. Away from [illegible]
3. Away from [illegible]
4. Away from [illegible]
5. Through [illegible]
(2) [illegible]
(3) [illegible]
(4) [illegible]
(5) [illegible]

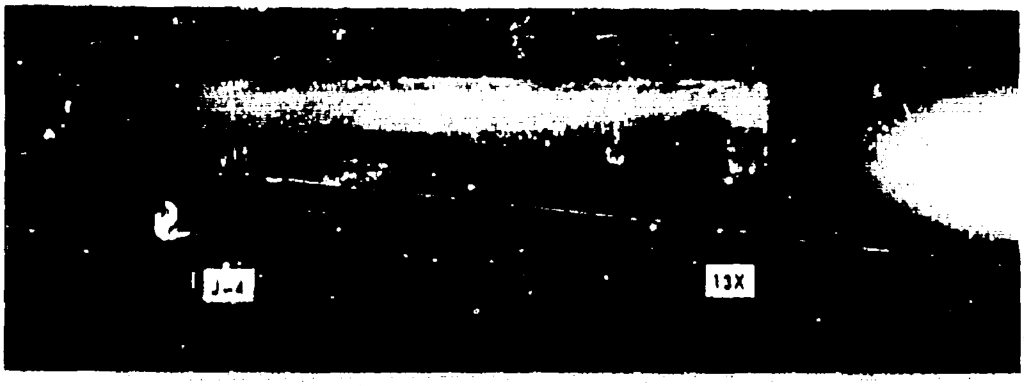

Figure 84 Welded Specimen J-4. Fracture Surface After Failure During 2nd Cycle. (Environmental-test conditions: 1600F, 6 ksi, salt; scheduled duration: 63 cycles) (H-63865)
Mag: 13X

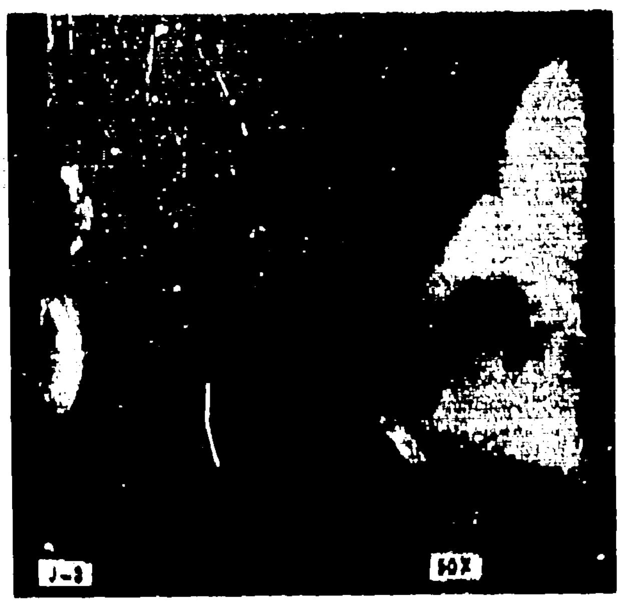

Figure 85 Welded Specimen J-3. Failed During 1st Cycle at Waspaloy - TD-Nickel Interfaces. (Environmental-test conditions: 1600F, 6 ksi, salt; scheduled duration: 63 cycles) (EM-3074-2)

Etchant: 5 gm $FeCl_3$ + 2 ml HCL + 99 ml CH_3CH_2OH Mag: 50X

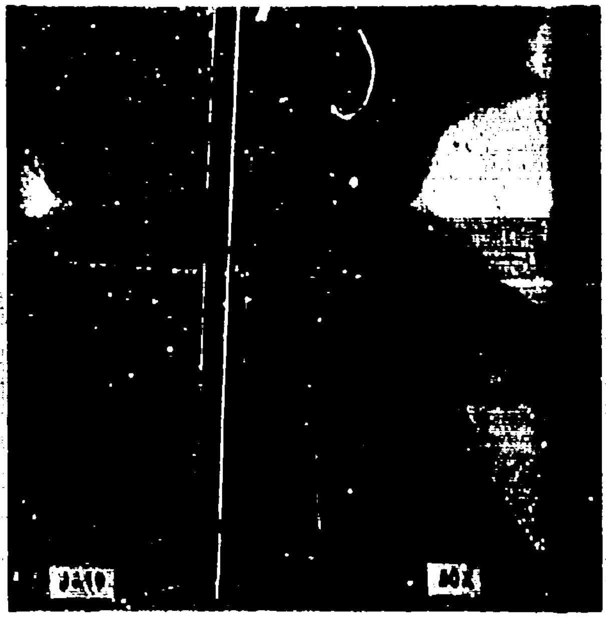

Figure 86 Welded Specimen J-19. Photomicrograph of Section Through Weld and Parent Metal. (Specimen not subjected to environmental test) (EM-3074-1)

Etchant: 5 gm $FeCl_3$ + 2 ml HCL + 99 ml CH_3 CH_2 OH Mag: 50X

TD Nickel (Brazed) - Of the twelve brazed specimens subjected to environmental testing, six survived and six failed, none due to salt corrosion. This was a somewhat better performance than that for the welded specimens, as would be expected, because there was no joint in the brazed specimens. All of the six survivors had been exposed to the 1600-F condition.

The brazed and salted specimens exposed at 2000F experienced significant metal loss in the brazed area. Those which ruptured in 32 and 32.3 cycles (J-21 and J-22) were more severely affected than the two which survived for 15 and 18.9 cycles (J-25 and J-26), as shown in Figures 87 and 88. A photomicrograph of specimen J-21, Figure 89, revealed little oxide scale in the area of braze depletion, but heavy scale over the remaining portions of the specimen. The maximum scale depth measured was 0.008 inch on one side. Brazed specimens exposed at 2000F without salt (J-29 and J-30) experienced metal loss at the braze - parent-metal interface only (Figure 90). Microexamination revealed that oxidation had occurred at this interface and under the braze, but that the braze layer itself was relatively unaffected (Figure 91). Only a non-brazed, unsalted, control specimen (J-39) completed its scheduled number of cycles at the 2000-F condition. It was severely cracked and oxidized (Figure 92). As shown in Table XXVI, tensile and yield strengths were significantly reduced compared to those for unexposed material (J-32 and J-33). Thus, based on the aforementioned evidence, it was concluded that at 2000F oxidation of the base metal reduced the strength of TD nickel, but the alloy formed between parent metal and braze was less oxidation resistant than either the braze alloy or the undiluted parent metal. The salt apparently accelerated deterioration of the alloy formed at the braze - parent-metal interface, as evidenced in the photographs of salted and unsalted specimens referred to previously (Figures 88 and 90). Thus, extensive oxidation and consequent effective thinning of the brazed specimens increased unit stress in them to the rupture point.

Figure 87 Brazed Specimen J-21. Failed During 32nd Cycle. Note Extensive Metal Loss in Brazed Area (bracket). (Environmental-test conditions: 2000F, 4 ksi, salt; scheduled duration: 63 cycles) (H-63849) Mag: 15X

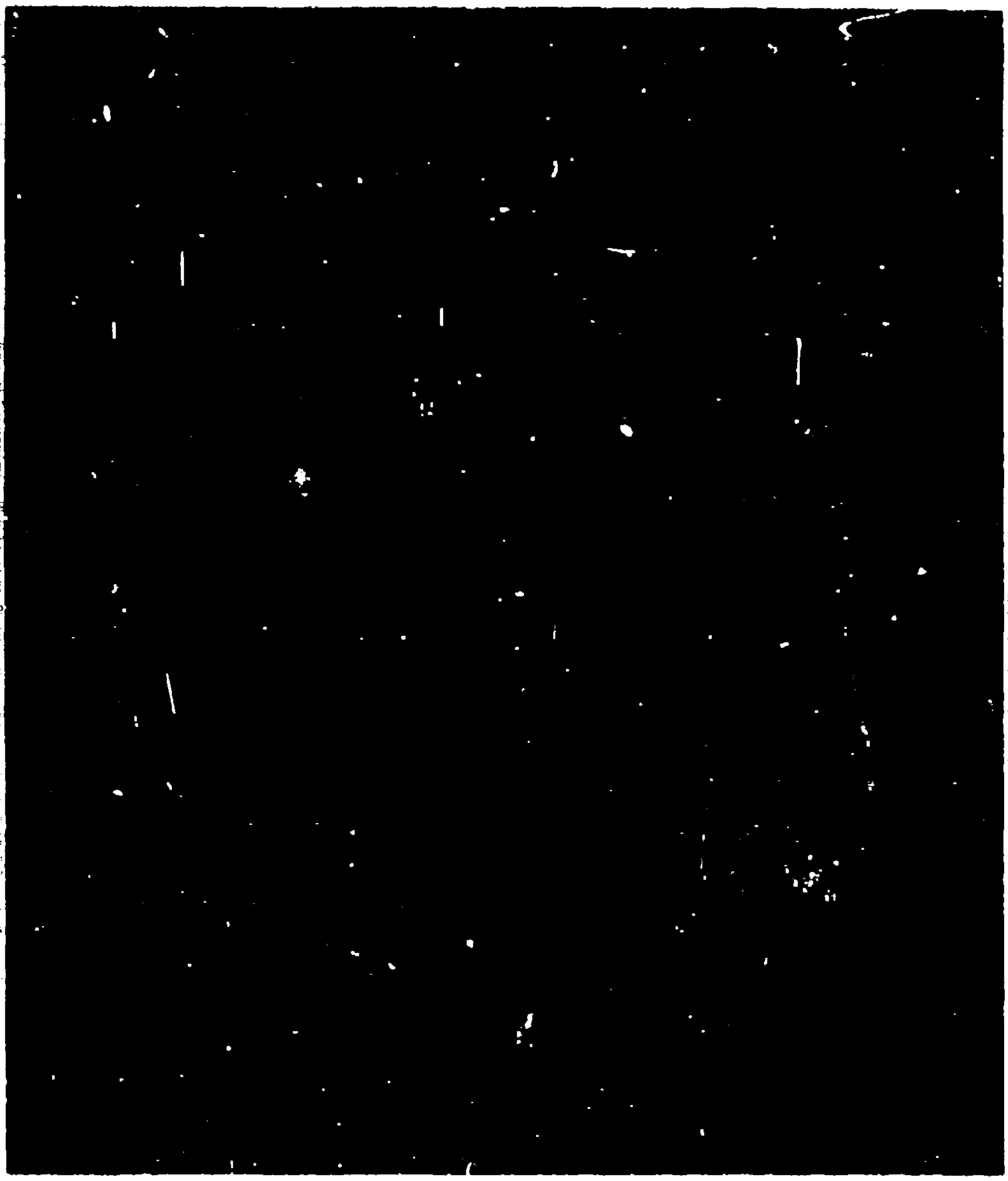

Figure 88 Brazed Specimen J-25. Failed During 15th Cycle. Note Metal Loss in Brazed Area (bracket). (Environmental-test conditions: 2000F, 5 ksi, salt; scheduled duration: 19 cycles) (H-63830)
Mag: 15X

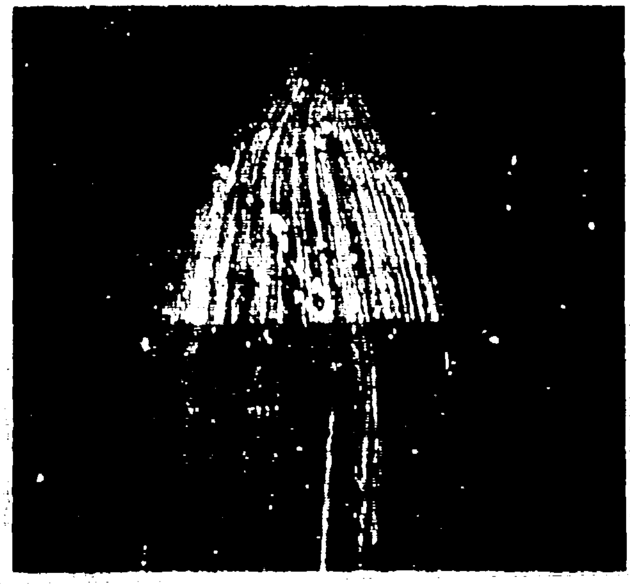

Figure 89 Brazed Specimen J-21. Failed During 32nd Cycle. Note Heavy Oxide Scale (arrow) and Braze Depletion (bracket). (Environmental-test conditions: 2000F, 4 ksi, salt; scheduled duration: 63 cycles)

(EP-2219-17)

Etchant: 5gm $FeCl_3$ + 2 ml HCL + 99 ml CH_3 CH_2 OH Mag: 50X

Figure 90 Brazed Specimen J-29. Failed During 15th Cycle. Note Metal Loss at Braze - Parent-Metal Interface (arrow). (Environmental-test conditions: 2000F, 4 ksi, no salt; scheduled duration: 63 cycles)

(H-63861) Mag: 7.5X

Figure 91 Photomicrographs of Brazed Specimen J-29. Failed During 15th Cycle. Note Extensive Oxidation at Braze - Parent-Metal Interface (arrow, top photo) and Degradation of Alloy Under Braze (bracket, bottom photo). (Environmental-test conditions: 2000F, 4 ksi, no salt; scheduled duration: 63 cycles) (EP-2219-4)(EP-2219-1)

Etchant: 5 gm $FeCl_3$ + 2 ml HCL + 99 ml CH_3 CH_2 OH Mag: 250X

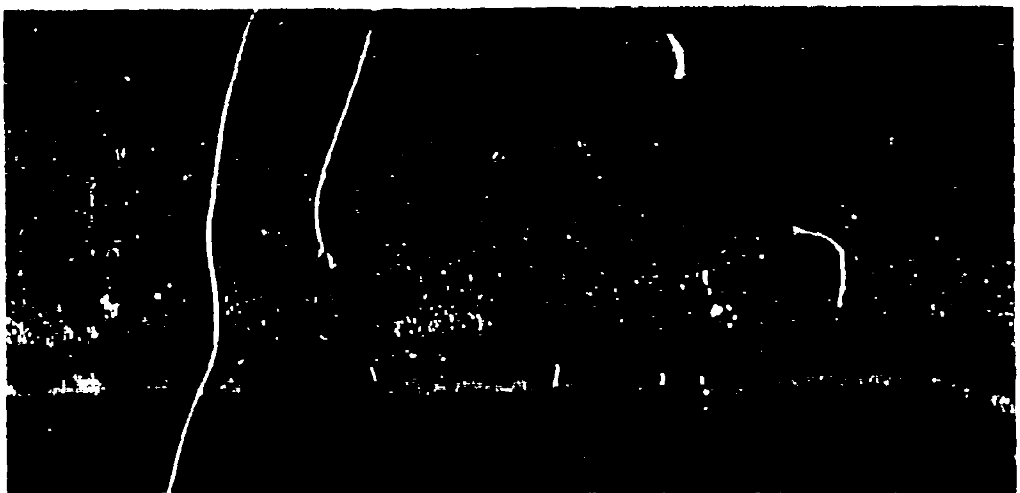

Figure 92 Non-Brazed Control Specimen J-39 Prior to Tensile Testing. Note Extensive Oxidation and Cracking. (Environmental-test conditions: 2000F, 4 ksi, no salt; duration: 63 cycles) (H-64191)
Mag: 7X

Brazed specimens exposed at 1600F did not deteriorate to the extent observed at 2000F. A slight scaling was apparent at the braze - parent-metal interface in salted specimens (Figure 93). Tensile properties of salted (J-23 and J-24) and unsalted (J-34 and J-35) specimens exposed at 1600F and 8.0 ksi for 63 cycles were comparable to each other. Thus, salt had no effect on the strength of the specimens at this temperature, nor was Type-(1) or Type-(3) corrosion observed. All specimens exposed at 1600F exhibited slightly lower tensile strengths than did unexposed material (J-32 and J-33).

B. Non-Destructive Inspection

The non-destructive-inspection methods utilized on all specimens in the environmental test program as possible aids in the detection of corrosion included radiographic and fluorescent-penetrant inspections, and ultrasonic, beta-ray-backscatter, and electrical-conductivity measurements prior to, during, and after environmental exposure. The results obtained from each of these methods are presented for each alloy in Tables XXVII through XXXVI, and are discussed briefly below. One reason for the wide scatter in inspection results, and in some instances no results, was the heavy scaling of the exposed specimens.

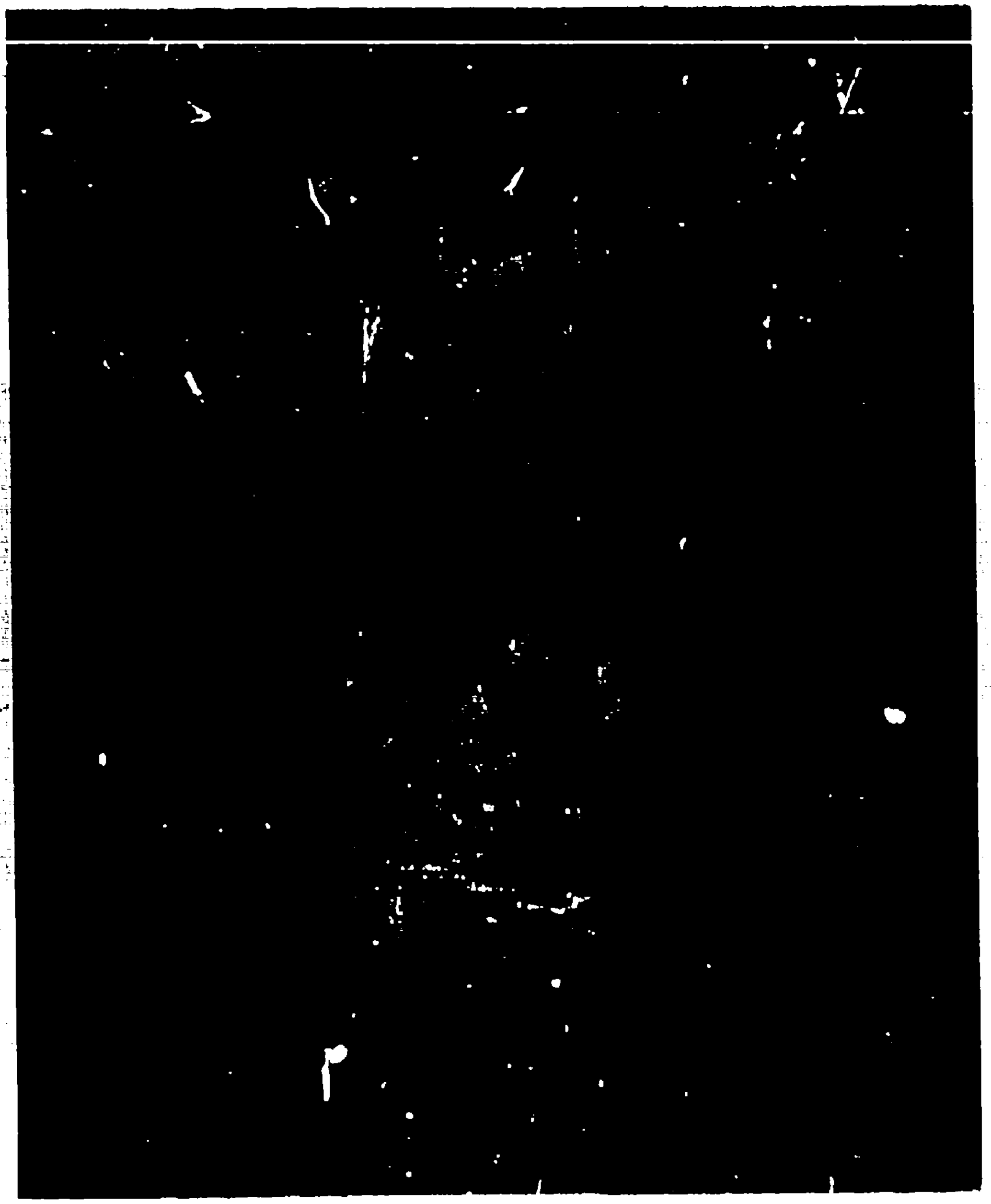

Figure 83 Brazed Specimen J-23 Prior to Tensile Testing. Note Light Scaling at Braze - Parent-Metal Interface (arrows). (Environmental-test conditions: 1600F, 8 ksi, salt; duration: 63 cycles) (H-64190)
Mag: 7X

TABLE XXVII

NON-DESTRUCTIVE-TEST DATA FOR AM-350 ALLOY SPECIMENS

TABLE XXVIII

NON-DESTRUCTIVE-TEST DATA FOR AM-355 ALLOY SPECIMENS

[illegible]

TABLE XXIX

NON-DESTRUCTIVE-TEST DATA FOR PH15 - 7Mo ALLOY SPECIMENS

TABLE XXX

NON-DESTRUCTIVE-TEST DATA FOR PH14 - 8Mo ALLOY SPECIMENS

TABLE XXXI

NON-DESTRUCTIVE-TEST DATA FOR HASTELLOY-X ALLOY SPECIMENS

TABLE XXXII

NON-DESTRUCTIVE-TEST DATA FOR RENÉ-41 ALLOY SPECIMENS

[illegible]

TABLE XXXIII

NON-DESTRUCTIVE-TEST DATA FOR UDIMET-700 ALLOY SPECIMENS

TABLE XXXIV

NON-DESTRUCTIVE-TEST DATA FOR A-286 ALLOY SPECIMENS

[illegible]

TABLE XXXV

NON-DESTRUCTIVE-TEST DATA FOR GREEK-ASCOLOY ALLOY SPECIMENS

[illegible]

TABLE XXXVI

NON-DESTRUCTIVE-TEST DATA FOR TD-NICKEL ALLOY SPECIMENS

Corrosion was visible in fourteen specimens following tensile testing. These were: A-1, A-3, A-21, A-34, C-21, C-24, C-29, C-30, D-21, D-29, D-30, D-34, F-22 and F-26. Welded René-41 and A-286, and brazed Hastelloy-X, Udimet-700, and A-286 specimens experienced degradation of tensile properties, but no Type-(1) or Type-(3) corrosion was detected. A chart summarizing the findings of the non-destructive testing of the fourteen specimens is presented in Table XXXVII. Discussion of these findings follows.

TABLE XXXVII

SUMMARY OF NON-DESTRUCTIVE-TEST RESULTS FOR SPECIMENS EXPERIENCING TYPE-(1) AND TYPE-(3) CORROSION

	Non-Destructive Inspection Method (1)					
Specimen	Radiographic	Fluorescent Penetrant	Ultrasonic	[illegible]	Electrical Conductivity (2)	Remarks
A-1	OK	OK	OK	OK		Failure in weld joint
A-3	OK	OK	OK	OK		Failure in weld joint
A-21	Ind.	B-O	OK	OK		Failure in parent metal
A-34	Ind.	B-O	OK	OK		Failure in parent metal
C-21	OK	B-O	OK	OK		Failure in parent metal
C-24	OK	B-O	OK	OK		Failure in parent metal
C-29	OK	B-O	Ind.	OK		Failure in parent metal
C-30	OK	B-O	OK	OK		Failure in braze region
D-21						Failed before 10 cycles
D-29						Failed before 10 cycles
D-30						Failed before 10 cycles
D-34						Failed before 10 cycles
F-22	OK	W	W	W	OK	Failure in braze region
F-26	OK	W	W	W	OK	Failure in parent metal

Notes: (1) Explanation of symbols:
OK = No indication found
W = Inspection waived
Ind = Indication found
B-O = Bleed-out
(2) This method applicable to non-magnetic specimens only.

Radiographic - Ten of the fourteen specimens identified above were inspected radiographically at intervals in their scheduled test programs. The other four specimens failed during their initial test cycles. Radiographs of eight of the ten failed to reveal indications of corrosion; those of the remaining two specimens revealed indications, but not the discolored cracks, and the post-exposure, tensile-test failure locations were not coincident with the indications.

Fluorescent Penetrant - Eight of the ten corroded specimens which had been inspected radiographically were also examined by the fluorescent-penetrant method (post-exposure inspection of brazed René 41 was waived because of heavy surface oxide). Six of the eight evidenced bleed-out, but not at the discolored cracks; there was no indication for two. With reference to the latter two specimens, failure at post-exposure tensile test occurred in the weld region (the region which was covered by the inspections). As for the remaining six, all but one of the tensile-test failures occurred outside of the brazed region where the bleed-out was located; the bleed-out in the excepted instance was not necessarily associated with the corrosion ultimately detected after destructive testing.

Ultrasonic - Ultrasonic inspection of the eight specimens referred to in the preceding paragraph disclosed one specimen with an indication and seven without. The specimen with the indication failed outside the joint region at post-exposure tensile test; of the other seven specimens, four failed outside the joint region and three failed inside.

Beta-Ray Backscatter - Analysis of the data taken by this method failed to reveal any correlation with the findings of either the other non-destructive methods or post-exposure tensile testing.

Electrical Conductivity - This method was applicable only to the non-magnetic alloy specimens. The only non-magnetic alloy exhibiting Type-(1) corrosion was brazed René 41. As shown in Table XXXII, slight changes in conductivity readings were recorded for the two specimens exhibiting corrosion (F-22 and F-26). However, the magnitude of change involved in these specimens was considered insignificant, as were the results for other non-magnetic alloys which exhibited any type of corrosion.

In summary, it may be stated that extensive investigations of five possibly useful non-destructive methods for detecting incipient corrosion, or for determining degradation of properties, revealed that, insofar as the program covered by this report was concerned, none would be a reliable indicator of incipient corrosion or property degradation in parts made from the ten alloys considered in the program.

C. Summary of Results

The significant results of the testing conducted under the environmental test program are listed below:

(1) The alloys which exhibited corrosion, the types of corrosion, and the temperatures at which corrosion was found, are indicated in Table XXXVIII.

TABLE XXXVIII

SUMMARY OF TYPES OF CORROSION FOUND FOR ALLOYS TESTED

Material and Joint		Salt Corrosion(a)			Other Corrosion
		Type (1)	Type (2)	Type (3)	
AM 350	Weld	800F		800F 600F	
AM 350	Braze	800F		800F	
PH15-7Mo	Braze				800F(b) 600F
PH14-8Mo	Braze				800F(b)
Hastelloy X	Braze		2000F 1600F		
René 41	Weld		1800F 1600F		
René 41	Braze	1800F	1800F		1600F(c)
Udimet 700	Weld				1600F(d)
Udimet 700	Braze		1600F		
A 286	Weld		1200F		
A 286	Braze		1200F		
TD Nickel	Braze				2000F(e)

Notes: (a) See Section VI for identification of types of salt corrosion
(b) Corrosion indications were found on both salted and unsalted specimens in the areas affected by the brazing process
(c) Galvanic corrosion was evident on brazed and salted specimens
(d) Evidence of sulfidation on one specimen
(e) Salt accelerated deterioration at braze - parent-metal interface

(2) Three types of salt corrosion were observed in test specimens:

Type (1) Evidenced by localized discoloration on the fracture surface, indicating the existence of a crack during exposure of the specimen to elevated temperatures.

Type (2) Evidenced by post-exposure, room temperature, tensile-property degradation.

Type (3) Evidenced by unusual cracking during post-exposure, room temperature, tensile testing.

(3) Four other types of corrosion were observed in test specimens:

1. PH 15-7 Mo and PH 14-8 Mo brazed specimens, both salted and unsalted, were corroded in regions where Green Stop-off had been applied.

2. Galvanic corrosion was found on brazed and salted Rene' 41 specimens tested at 1600F.

3. Evidence of sulfidation was found on one Udimet 700 welded specimen tested at 1600F.

4. Salt accelerated the deterioration of the alloy formed at the braze-parent metal interface of TD nickel specimens tested at 2000F.

(4) The stainless steels (AM 350, AM 355, PH 15-7 Mo and PH 14-8 Mo) were not susceptible to Type (2) salt corrosion. The superalloys, except for Greek Ascoloy and TD nickel were susceptible to Type (2) salt corrosion.

Only AM 350 and brazed Rene' 41 were susceptible to Type (1) or Type (3) salt corrosion.

Rene' 41 over aged at both test temperatures, 1600F and 1800F.

Welded TD nickel specimens failed prematurely because of lack of penetration in the weld.

(5) The room-temperature tensile strengths of welded and brazed AM 350, AM 355, PH 15-7 Mo, PH 14-8 Mo, and A-286, increased during exposure to elevated temperature, with larger increases occurring at the higher temperatures. This indicates that additional aging occurred during environmental exposure.

(6) For the joined and salted materials listed below, the post-exposure room-temperature tensile strengths decreased with increasing exposure temperature.

Brazed Hastelloy X
Welded Rene' 41
Brazed Udimet 700

(7) The strengths of the following welded and brazed materials were less after exposure to the higher temperature for 63 cycles with salt than were the strengths of unjoined materials.

Welded AM 355
Welded and brazed PH 15-7 Mo
Brazed Hastelloy X
Brazed Rene' 41
Welded A-286
Brazed A-286

(8) No significant correlation was found between non-destructive inspection data and the corrosion observed as a result of post-exposure tensile testing.

(9) Table XXXIX presents what are considered to be acceptable design limits for the ten alloys when welded and brazed parts made from them are to be exposed to a salt atmosphere. These limits are based on survival of all test specimens during environmental exposure at the conditions listed in the table.

TABLE XXXIX

ACCEPTABLE DESIGN LIMITS FOR ALLOYS COMPLETING ENVIRONMENTAL EXPOSURE

Material and Joint		Stress Level (ksi)	Temperature (F)	Cycles Exposed
AM 350	Weld	117	800	63
		132	600	63
	Braze	132	600	63
AM 355	Weld and Braze	117	800	63
		130	600	63
PH15-7Mo	Weld	130	800	63
		160	600	63
	Braze	160	600	19
PH14-8Mo	Weld	148	800	63
		160	600	63
	Braze	160	600	19
Hastelloy X	Weld and Braze	3	1600	63
		3.5	1600	19
René 41	Weld	4	1800	19
		13	1600	63
		17	1600	19
	Braze	3	1800	63
		4	1800	19
		17	1600	19
Udimet 700	Weld	29	1600	19
	Braze	5	1900	19
		24	1600	63
		29	1600	19
A 286	Weld and Braze	30	1200	63
		35	1200	19
		83	800	63
Greek Ascoloy	Weld and Braze	83	800	63
		95	600	63
TD Nickel	Braze	8	1600	63
		9	1600	19

VII

REPAIR BY WELDING AND BRAZING

It had been planned to evaluate welding and brazing as means of repair of specimens which had been weakened by corrosion resulting from severe environmental conditions, provided that the degradation was not too severe. This assumed the following:

(1) That any degradation of properties would be accompanied by Type-(1) salt corrosion or other evidence of corrosion;

(2) That non-destructive inspection methods could locate these evidences of corrosion;

(3) That areas of corrosion could be removed and replaced by weld or braze material; and

(4) That the repaired specimens could then be tensile tested to measure their properties.

No repair work was possible because no correlation was found between degradation of properties (Type-(2) corrosion) and any other type of corrosion; no non-destructive inspection method was found for positively locating evidence of incipient corrosion; and, in the cases where visible corrosion was evident, such corrosion was too extensive for repair.

VIII

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are based upon the results of the testing reported herein and are limited by the specifications of such testing.

1. Welding decreases the post-exposure, room-temperature, tensile strenghts of PH15 - 7Mo, A 286, and TD Nickel (based on unsalted specimens at maximum temperature and number of cycles); it does not affect AM 350, AM 355, PH14 - 8Mo, and Greek Ascoloy; and its effects on Hastelloy X, René 41, and Udimet 700 are uncertain.

2. Brazing decreases the post-exposure, room-temperature, tensile strenghts of PH15 - 7Mo, Udimet 700, and TD Nickel (based on unsalted specimens at maximum temperature and number of cycles); it does not effect AM 355, Hastelloy X, Rene 41, and A 286; and its affects on AM 350, PH14 - 8Mo, and Greek Ascoloy are uncertain.

3. Welding results in the susceptibility of AM 350 to Type-(1) and Type-(3) corrosion at maximum temperature and number of cycles; it does not have this effect on the other investigated materials.

4. Brazing results in the susceptibility of AM 350 and René 41 to Type-(1) and Type-(3) corrosion at maximum temperature and number of cycles; its effect in this respect on Greek Ascoloy, TD Nickel, PH15 - 7Mo and PH14 - 8Mo is uncertain; and it has no such effect on the other investigated materials.

5. AM 350, Hastelloy X, René 41, Udimet 700, A 286, and TD Nickel, in the brazed form, are more susceptible to salt corrosion than in the welded form.

6. Corrosion of brazed PH15 - 7Mo and PH14 - 8Mo is caused by the materials associated with the brazing process.

7. Sulfidation of the investigated nickel-base alloys is not significant under the evaluation conditions.

8. TD Nickel must be coated for use at 2000F in air.

9. Repair of salt corrosion in the alloys which were tested is not feasible.

10. The non-destructive testing techniques used are not effective in detecting corrosion of the types which were experienced.

The following recommendations are made for any follow-on work to this program.

1. Measurement of strain which occurs during environmental exposure.

2. Exploration of lower temperatures and/or stress levels for materials which failed during environmental exposure, to establish design limits.

3. Investigation of the individual and combined effects of the materials associated with the brazing processes.

4. Testing of TD Nickel in the coated condition.

5. Determination of the temperature limits within which galvanic corrosion will occur in brazed René 41 in a salt environment.

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13. ABSTRACT

Temperature-cycling tests were conducted on specimens of ten alloys representative of materials in current use in high-speed aircraft. Half of the specimens were welded and half were of one-piece construction with a braze-material patch. All specimens, with the exception of some controls, had salt patches extending over the welded or brazed regions. The specimens were tested under constant load during temperature cycling. The test conditions were such as could result in corrosion and consequent degradation of mechanical properties of the alloys. Subsequent to environmental exposure, room-temperature tensile tests were performed, to determine the degree of alloy deterioration. Non-destructive methods of inspection were evaluated and found to be ineffective for detecting the incipient corrosion which was encountered. Analyses of the environmental-test data were conducted and the relative influence of combinations of exposure conditions on the production of corrosion in specimens was ascertained. Design limits are presented for all the materials which were investigated. It was not possible in this program to evaluate the capability of welding or brazing for restoring the mechanical properties of alloys after such properties have been degraded by corrosion. Recommendations are made as to the directions which any further investigations into the corrosion phenomenon should take.

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