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STRUCTURAL MATERIALS DIVISION

STRESS-CORROSION CRACKING OF HIGH-STRENGTH ALLOYS

Contract DA-04-495-ORD-3069

A Report To

U.S. ARMY ORDNANCE CORPS
FRANKFORD ARSENAL

Report No. 0414-01-9 (Quarterly) May 1963 6

AEROJET GENERAL

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AEROJET-GENERAL CORPORATION

A SUBSIDIARY OF THE GENERAL TIRE & RUBBER COMPANY

This is the ninth in a series of quarterly progress reports submitted in partial fulfillment of the contract. It constitutes the third quarterly progress report for the 1-year continuation of the original 2-year program.

This report covers the period from 1 January through 31 March 1963. It was written by R. B. Setterlund, who was supervised by A. Rubin.

Approved by

P. L. Jordan, Head
Metallics and Refractories Department
Structural Materials Division

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I. OBJECTIVES

The objectives of this program are

A. Investigation of the stress-corrosion-cracking characteristics of at least three new high-strength alloys of interest for rocket-motor-case applications (6Al-4V titanium, 18%-nickel maraging steel, and 20%-nickel maraging steel), in addition to limited testing of vacuum-melted 9Ni-4Co steel

B. Study of the environmental parameters that could affect the rate and extent of stress-corrosion cracking

C. Determination of the effect of material parameters (composition, strength level, welding, and microstructure) on stress-corrosion susceptibility

D. Continuation of the evaluation of protective coatings and other techniques for the prevention of stress-corrosion cracking.

II. SUMMARY

Test results showed that, under all the test conditions of this program, the 6Al-4V titanium alloy is immune to stress-corrosion cracking in the annealed, quenched-and-aged, and as-welded conditions.

The 20%-nickel grade of maraging steel was found to be highly susceptible to stress-corrosion cracking in the annealed-and-aged condition. This same alloy, when cold-worked 50 to 75% before aging, was found to be only mildly susceptible to stress-corrosion cracking. The most favorable mechanical properties were attained after 50% cold reduction and subsequent aging. The welded-and-aged alloy was found to be extremely susceptible to stress-corrosion cracking in the weld-heat-affected zone.

The 18%-nickel grade of maraging steel was also found to be susceptible to stress-corrosion cracking, which was found to occur more rapidly in the

II Summary (cont.)

annealed-and-aged material than in the 50% cold-worked-and-aged material. It was also found to occur more rapidly in the higher-strength (i.e., higher-titanium) heats. This material has not yet been tested in the welded condition.

III. WORK PROGRESS

A. INTRODUCTION

In the original 2-year investigation of the stress-corrosion-cracking characteristics of high-strength alloys, a number of steels of then-current interest for rocket-motor-case applications were evaluated. Since then the need for alloys of still higher strength in the rocket industry has focused attention on the maraging steels. The third-year program (see Table 1) was therefore directed to the study of the stress-corrosion-cracking susceptibility of a currently used titanium alloy (Table 2), two maraging steels (Table 3), and a new 9Ni-4Co alloy.

The test environments, substantially the same as those in the original 2-year investigation, are (1) distilled water, (2) tap water, (3) salt water, (4) sodium-dichromate-inhibited water, (5) soluble-oil-inhibited water, (6) air, (7) high-humidity atmosphere, (8) trichloroethylene, (9) cosmoline, and (10) solid propellant. These environments are considered to be representative of those to which rocket-motor cases would normally be exposed during fabrication, processing, or storage. One additional environment is included in the new program, that of seacoast exposure.

Bent-beam, U-bend, and center-notch specimens are being used in the investigation. The evaluations of results include microstructural studies, using both standard metallographic and electron-microscope techniques, in attempts to associate the failure mechanism with specific microstructural characteristics of the materials.

Protective coatings and surface treatments to prevent stress-corrosion cracking are also being evaluated.

B. TEST PROCEDURES

1. Bent-Beam Test

The bent-beam test is the primary method used in this program. A total of 595 tests of this type are being conducted. Figure 1 shows an insulated bent-beam fixture with test samples mounted. Polycarbonate blocks 7.000 $\pm$0.002 in. apart, attached to a stainless-steel holder, support the test specimen and insulate it from the holder. Specimens are machined to exact lengths to produce a maximum calculated outer-fiber stress that amounts to 75% of the mean 0.2%-offset yield strength.

A four-point loading device is used to place the specimens into the holders. The use of four-point loading in this pre-stressing device eliminates possible local plastic deformation (which may have occurred during some earlier tests using a three-point loading fixture). Samples that were loaded into fixtures and then unloaded by means of the four-point device showed no apparent residual distortion, which indicated that the yield strength of the material had not been exceeded during stressing.

2. U-Bend Test

Figure 2 shows a U-bend test sample. This test was used extensively in the initial 2-year program to accelerate failure times by producing stresses beyond the yield strength of the material. The U-bend test method is now being used only for the 6Al-4V titanium alloy because initial testing indicated that some of the maraging steels would not withstand the drastic distortion of a U-bend while in the fully aged condition. Although it is possible to give the samples a partial bend in the annealed condition and to complete the U-bend after subsequent aging, it is believed that this procedure would not represent a realistic condition for study. The center-notch test described below is being used for acceleration of failure times.

3. Center-Notch Test

The configuration used in the center-notch test is shown in Figure 3. It consists of a 1-3/4 by 8-in. tensile specimen containing a central

III Work Progress, B (cont.)

notch, which is produced in a two-step process: (a) a 0.06 by 0.57-in. slot is Elox-machined and extended at each end by very narrow Elox-machined notches of 0.001-in. root radii, and (b) these notches are extended by means of fatigue cycling to obtain fatigue cracks of controlled dimensions.

When a specimen of this type is stressed, the elastic field parameter (K, in ksi$\sqrt{\text{in.}}$) at the tip of the crack is represented by

$$K = \sigma \left(W \tan \frac{a\pi}{W}\right)^{1/2}$$

where W is the specimen width (in.), a is one-half of the total crack length (in.), and σ is the nominal stress (ksi). Simultaneously, the crack-extension force (G_c, in in.-lb/in.^{2}) may be obtained from

$$G_c = \frac{K_c^2}{E}$$

where E is the elastic modulus of the material and K_c is the critical value of K at which crack propagation occurs in rapid tensile testing.

These center-notch specimens are stress-corrosion tested in Baldwin creep-test machines (Figure 4). Dead-weight loading is applied to a 20 to 1 lever arm to give a K value at the crack tip amounting to 75% of the K_c value. The test solution is applied in a polyethylene cup cemented to the specimen in the notched area before loading. An automatic timing device is used to record the time to failure.

C. TEST ENVIRONMENTS

The environments described below were used to study stress-corrosion-cracking susceptibility.

1. Laboratory Air

This environment was used as a standard for comparison with other environments. The temperatures ranged from 70 to 78°F, and the relative humidity ranged primarily from 35 to 50%. No stress-corrosion failures have yet occurred in this environment, even with the most susceptible alloys.

III Work Progress, C (cont.)

2. Distilled Water

This environment was also used as a standard for comparison with other environments. The pH of the distilled water was found to be 7.0. Continuous aeration was maintained with filtered air during the test. This environment was found to cause rapid stress-corrosion cracking in susceptible alloys.

3. Aerated Tap Water

Tap water represents the medium frequently used to clean solid-propellant rocket-motor cases. It is also used in the hydrostatic testing of pressure vessels, particularly chambers constructed of corrosion-resistant alloys. Azusa well water with a pH of 7.6 was used in the Aerojet tests; the water analysis is summarized in Table 4. It was found that, in most cases, the tap water was a less severe environment than distilled water.

4. Aerated Salt Water

An aerated 3% solution of sodium chloride in distilled water was used to simulate a severe marine environment. It was found, however, that the addition of NaCl made the distilled water only slightly more aggressive in promoting stress-corrosion cracking, even though there was a noticeable increase in corrosion. The pH of this solution was 7.0.

5. High Humidity

Samples are placed in water-saturated air at 130 to 140°F to simulate a severe atmospheric condition.

6. Seacoast Exposure

Samples were placed on an outdoor test rack (Figure 5) at the Aerojet Newport Beach test facility for testing in a natural seacoast environment. This rack, placed on a rooftop approximately 200 yards from the beach, faced the beach without obstruction. The results obtained thus far correlate well with laboratory tests of the same alloys.

7. Aerated Chromate Solution

This environment, created by 0.25% by weight of sodium dichromate dissolved in distilled water, represents the medium frequently used in flushing solid-propellent rocket-motor cases and in the hydrostatic testing of pressure vessels, particularly those constructed of low-alloy steels. The pH of this solution was between 4.5 and 5.0.

8. Soluble-Oil Solution

This environment, a distilled water solution of 4% by volume of Chevron soluble oil, represents one of the fluids used in the hydrostatic testing of pressure vessels. Aeration was discontinued in this test medium because of foaming. The pH was between 9.5 and 10.0.

9. Cosmoline

Rust-inhibiting oil conforming to MIL-C-14201A, Grad 2, was used to represent the rust-inhibiting compound sometimes used for rocket-motor cases during manufacture, transit, and limited storage prior to propellant installation.

10. Trichloroethylene

This is a chlorinated, degreasing solvent commonly used on rocket-motor cases.

D. ALLOY PROPERTIES

1. 6Al-4V Titanium

This high-strength titanium alloy is being widely used for pressure vessels and rocket-motor cases. It has excellent fabricability and can be heat-treated to high strength levels. The chemical and mechanical properties of the heat of the alloy that was tested are shown in Table 3. The sample was tested in three metallurgical conditions: annealed, quenched and aged, and as-welded.

The annealed condition employed in the testing was the condition in which the alloy was received. No further thermal treatment was employed, but 0.010 in. was ground from each side of the samples.

III Work Progress, D (cont.)

The quenched-and-aged condition was attained by means of a 1675°F solution-anneal followed by a water-quench and an 8-hour aging treatment at 900°F. Some distortion of the samples was found to occur during quenching, but this was largely overcome by aging while the specimens were clamped tightly in a stainless-steel fixture. After aging, 0.010 in. was ground from each side of the specimen.

Some of the annealed material was welded using the TIG (tungsten-inert-gas) process with commercially pure titanium filler wire. The samples were exposed in the as-welded condition with a 30% weld reinforcement.

2. 20%-Nickel Maraging Steel

This is a high-strength steel that will attain desired strengths in a single aging treatment. Its chemical and mechanical properties are shown in Table 2. One heat of 20%-nickel maraging steel was tested in four conditions: annealed and aged; 50% cold-worked and aged; 75% cold-worked and aged; and welded and aged. Figure 6 shows the effect of prior cold-work on the mechanical properties of the aged material. All aging was performed at 850° for 4 hours. With the welded and the annealed samples, aging was preceeded by a 1-hour stabilizing treatment at -100°F.

Welding was performed on the 20%-nickel steel with an automatic TIG welder without filler metal. Mechanical tests indicated an 85% joint efficiency. Low G_c values were obtained with this alloy, indicating a high degree of notch sensitivity.

3. 18%-Nickel Maraging Steel

This alloy has a nominal composition of 18% nickel, 9% cobalt, and 5% molybdenum; it is receiving increased attention for application in the aerospace industry. Because of the high interest in this alloy, five heats of this material are being tested. Two were purchased for this program, and the other three were remnants from an earlier Aerojet program. The chemical and mechanical properties are given in Table 2.

Figure 7 shows the effect of titanium content on the mechanical

III Work Progress, D (cont.)

properties of annealed material aged at 900°F for 3 hours. These data show that increases in titanium content will increase the ultimate and yield strengths of maraging steel with only slight lowering of the reduction-of-area and notch-sensitivity values. Figure 8 shows how the yield and ultimate strengths may be raised even more by cold reduction prior to aging, again at the expense of a lower G_c value; however, even the lowest G_c value obtained with the 18%-nickel steel (156 in.-lb/in.^{2} at a yield strength of 354 ksi) is almost 3 times higher than the highest obtained with the 20%-nickel alloy (58 in.-lb/in.^{2} at 291 ksi).

The 18%-nickel steel was welded by means of the TIG process without filler metal. Mechanical tests indicated a 94% joint efficiency.

4. 9Ni-4Co Vacuum-Cast Steel

This vacuum-melted steel is reported to be in the development stage. It reportedly has exceptional notch toughness and high yield and ultimate strengths. Aerojet has ordered material at carbon levels of 0.25 and 0.45%. Only the lower-carbon material has been received; it is now under evaluation for mechanical properties, and limited stress-corrosion testing will soon be initiated.

5. H-11 Steel

This alloy was found to be the most susceptible to stress-corrosion cracking of any alloys tested in the initial 2-year program. Consequently, it is being used as a basis for the evaluation of protective coatings for preventing stress-corrosion failures. The material is heat-treated to its most susceptible condition as follows: at 1900°F for 40 min, followed by an air-quench and then 950°F aging for 3 hours.

IV. TEST RESULTS

A. BENT-BEAM TESTS

Results of the bent-beam tests presented in Tables 5 through 14 are summarized below.

1. 6Al-4V Titanium

No failures have been observed with the 6Al-4V titanium alloy in any of the three metallurgical conditions tested.

2. 20%-Nickel Maraging Steel

In the annealed-and-aged condition the 20%-nickel maraging steel was found to crack rapidly in distilled-water, salt-water, high-humidity, trichloroethylene, and seacoast atmospheres. The cracking was found to follow a branching pattern, as shown in Figure 9. Photomicrographs (Figure 10) indicated that the cracking follows an intergranular pattern.

When the alloy was cold-worked before aging, a marked increase was noted in the time to failure. Random failures occurred after long exposure to distilled-water, tap-water, high-humidity, and seacoast atmospheres. The salt-water atmosphere (Table 7), which caused the most rapid failures with the annealed-and-aged material, has thus far caused no failures with the cold-worked-and-aged material. In addition, the tap-water environment (Table 6), which caused no failures with the annealed-and-aged material, caused some (long-term) failures in the cold-worked-and-aged material.

The welded material was found to have an even shorter time to failure than the annealed-and-aged material of the same heat. All failures were found to occur in the weld-heat-affected zone. Welded samples failed in tap-water, salt-water, distilled-water, trichloroethylene, and high-humidity environments.

3. 18%-Nickel Maraging Steel

In the annealed-and-aged condition the 18%-nickel maraging steel showed some failures in distilled-water, tap-water, salt-water, high-humidity, and seacoast atmospheres. In addition, one heat (Group I-1, see Table 1) was found to fail in the 0.25%-sodium-dichromate, 4%-soluble-oil, and trichloroethylene environments while showing negligible corrosion. In general it was found that the failure times were reduced as the titanium content was increased, although some exceptions were noted. Figures 11 and 12 present photomicrographs of failures of annealed-and-aged 18%-nickel maraging steel. As for the 20%-nickel steel, the cracking had a branchingintergranular pattern.

IV Test Results, A (cont.)

When the 18%-nickel steel was cold-worked before aging, the failure time was increased. At the same time, the mode of fracture appeared to change from intergranular to possible cracking along slip planes. Figures 13 and 14 show failures of 50% cold-worked-and-aged material.

The welded samples of the 18%-nickel maraging steel are now in the final stages of machining, testing is expected to being early in May.

4. Electron-Microscope Fractographs

Three fracture surfaces were selected for electron-microscope fractographs as shown in Figure 15. Parlodion replicas with chrome-carbon shading were used in making the fracture replicas. Because of the roughness of the surface, some difficulty was encountered in the stripping of the replicas. These fractographs are briefly described below.

a. H-11 Steel

The H-11 steel sample, shown at the top of Figure 15, has a single fracture at right angles to the surfaces of the specimen. This sample failed after 2.5 hours of exposure to aerated salt water.

Figure 16 shows a typical brittle fracture in a view taken from the center of the sample (View A indicated in Figure 15).

The view in Figure 17, taken from the corner of the sample at which the stress-corrosion fracture originated, shows some microstructure modeling that may have been caused by corrosion.

b. 20%-Nickel Maraging Steel

The 20%-nickel maraging steel specimen shown in the center of Figure 15 has a typical, branching, crack pattern. This sample is of the annealed-and-aged group (H-1) and failed after 1 hour in 0.25%-sodium-dichromate solution. It was selected for examination because of its complete freedom from rust.

Figure 18, a view taken from the area of final separation of sections of the sample, shows a definite ductile fracture.

IV Test Results, A (cont.)

Figure 19, a view taken from the central portion of the sample in the branching-pattern area, shows a brittle type of failure occurring in step-wise fashion.

Figure 20 presents a view taken from the area of fracture initiation, where the fracture is intergranular, with inclusions in the fracture domains.

c. 18%-Nickel-Maraging Steel

The 18%-nickel maraging-steel sample selected for study is sketched at the bottom of Figure 15. It was 50% cold-worked and aged and represents Group I-3. It failed after 626 hours in aerated distilled water.

Figure 21 presents a typical view in the stress-corrosion portion of the fracture and illustrates a brittle stepwise fracture along vaguely outlined domains.

B. CENTER-NOTCH TESTS

More than 100 center-notch tests have now been conducted. If time permits, 100 more tests will be added. The tests thus far have been confined to four environments: distilled water (Table 15), 3% NaCl solution (Table 16), 0.25% sodium dichromate solution (Table 17), and 4% soluble oil (Table 18).

1. <u>6Al-4V Titanium</u>

No failures have occurred in center-notch testing of this alloy in any of the four environments.

2. <u>20%-Nickel Maraging Steel</u>

Annealed-and-aged material (Group H-1) failed rapidly in the distilled-water and salt-water environments. It did not fail in the chromate and soluble-oil tests, thus supporting the results of the bent-beam tests.

Tests at various loads (Table 16) show that the time to failure is a linear function of the K value for that test

The 75% cold-worked-and-aged material (Group H-3) has a much longer time to failure than the annealed-and-aged material in the distilled-

IV Test Results, B (cont.)

water and salt-water environments.

3. <u>18%-Nickel Maraging Steel</u>

Both the annealed-and-aged and 50% cold-worked-and-aged materials were found to fail in salt-water, distilled-water, and chromate environments (in order of severity). The time to failure in the salt-water environment (Table 16) was found to decrease with decreasing K_c values for the test materials. No tests have been conducted thus far in a 4%-soluble-oil environment.

At a given titanium level, the time to failure is shorter for the cold-worked-and-aged material than for the annealed-and-aged material in the center-notch test; the results are reversed in the bent-beam tests. These data suggest that the longer life of the cold-worked-and-aged bent-beam samples may result from residual compressive stresses at the surface rather than a higher inherent resistance to stress-corrosion fracture.

C. COATING-EVALUATION TESTS

Table 19 presents results of the coating-evaluation program. These data will be reviewed more completely when a longer seacoast-exposure time is attained. It appears thus far that the most resistant coatings are the inhibited chromate epoxy Types 454-1-5 and 463-1-5. The pure vinyl coating also appears to show promise.

V. FUTURE WORK

The bent-beam tests will be continued as scheduled in Table 1. The last group of maraging-steel samples (Group I-W) is in the final stages of machining and testing will soon be initiated. Limited testing will also be started on the single heat of 9Ni-4Co vacuum-cast material that is available.

Center-notch testing will be continued up to the end of the contract period. The total number of tests performed will depend on the failure times of the samples now being tested. Most of the remaining tests that are planned will be conducted on 18%-nickel maraging steel. An attempt will be made to correlate the results of the center-notch tests with those of the bent-beam tests.

TABLE 1

MASTER PLAN, BENT-BEAM STRESS-CORROSION TESTS

Alloy	Processing Condition (Titanium Content of Maraging Steel Shown)	Strength Level, 0.2% Offset Yield (psi)	Specimen Code	Number of Test Environments: Distilled Water	Tap Water	3% NaCl Solution	0.2% Sodium Dichromate Solution	4% Soluble Oil Solution	High Humidity	Trichloro-ethylene	Cosmoline	Solid Propellant	Ambient Air	Sea Coast Atmosphere	Total
6Al-4V titanium	Annealed	138,000	G-1	3*	3	3	3	3	3	3	3	3	-	3	30
	Quenched and Aged	163,000	J-2	3	3	3	3	3	3	3	3	3	-	3	30
	Welded	135,000	G-W	2	2	2	2	2	2	2	2	-	2	2	20
	Total			8	8	8	8	8	8	8	8	6	2	8	80
20%-Nickel Maraging Steel	Annealed and Aged	291,000	H-1	3	3	3	3	3	3	3	3	3	3	3	33
	50% CW and Aged	321,000	H-2	3	3	3	3	3	3	3	3	3	3	3	33
	75% CW and Aged	298,300	H-3	3	3	3	3	3	3	3	3	3	3	3	33
	Welded and Aged	To be tested	H-W	3	3	3	3	3	3	3	3	3	3	3	33
	Total			12	12	12	12	12	12	12	12	12	12	12	132
18%-Nickel Maraging Steel	Annealed & Aged (0.62% Ti)	283,000	I-1	3	3	3	3	3	3	3	3	3	3	3	33
	50% CW & Aged (0.50% Ti)	302,400	I-2	3	3	3	3	3	3	3	3	3	3	3	33
	50% CW & Aged (0.62% Ti)	323,000	I-3	3	3	3	3	3	3	3	3	3	3	3	33
	Annealed & Aged (0.50% Ti)	249,900	I-4	3	3	3	3	3	3	3	3	3	3	3	33
	50% CW & Aged (0.40% Ti)	278,000	I-5	3	-	2	-	-	3	-	-	-	1	2	11
	Annealed & Aged (0.52% Ti)	255,400	I-6	3	-	2	-	-	3	-	-	-	2	3	13
	50% CW & Aged (0.52% Ti)	331,000	I-7	3	-	2	-	-	3	-	-	-	2	3	13
	Annealed & Aged (1.00% Ti)	323,200	I-8	3	-	2	-	-	3	-	-	-	1	2	11
	50% CW & Aged (1.00% Ti)	354,400	I-9	3	-	2	-	-	3	-	-	-	2	2	12
	Welded & Aged (0.50% Ti)	To be tested	I-W	3	3	3	3	3	3	3	3	3	3	3	33
	Total			30	15	23	15	15	30	15	15	15	23	27	225
9 Ni-4 Co Vacuum-Cast Alloy	Aged (0.25-0.30% C)	To be tested	J-1	3	3	3	3	3	3	3	3	3	3	3	33
	Aged (0.40-0.45% C)	To be tested	J-2	3	3	3	3	3	3	3	3	3	3	3	33
	Total			6	6	6	6	6	6	6	6	6	6	6	66
H-11 Steel (Coating Tests)	Application of Various Protective Coatings			-	-	37	-	-	29	-	-	-	-	26	92
	Total			56	41	86	41	41	85	41	41	39	43	79	595

*Number of replicate tests conducted.

TABLE 2

CHEMICAL ANALYSIS AND MECHANICAL PROPERTIES OF MARAGING STEELS

Supplier	Heat No.	Mill-Certified Analysis, % C	Mn	P	S	Si	Ni	Co	Mo	Al	Cb	Cr	Zr	Ti	Ca	B
Allegheny-Ludlum	W-24254	0.009	0.09	0.002	0.005	0.06	20.41	--	-	0.29	0.39	-	0.002	1.40	0.004	0.003
↓	W-24178	0.012	0.01	0.003	0.005	0.01	18.69	8.90	4.92	0.029	-	-	0.003	0.62	0.006	0.002
↓	477	0.018	0.002	0.006	0.004	0.024	18.29	9.10	4.95	0.089	-	-	<0.004	0.40	<0.0006	<0.003
↓	448	0.029	0.002	0.004	0.008	0.009	18.51	8.48	4.92	0.089	-	-	<0.004	0.52	<0.0006	<0.003
Allegheny-Ludlum	476	0.020	0.002	0.006	0.005	0.014	18.60	9.05	4.90	0.078	-	-	<0.004	1.00	<0.0006	<0.003
Republic Steel	3960502	0.020	0.08	0.007	0.006	0.15	18.48	7.00	4.84	0.21	-	0.10	0.035	0.50	Added	0.0036

Heat No.	Prior Condition	Aging Treatment	Table 1 Code No.	Transverse Mechanical Properties (Aerojet Tests) 0.2%-Offset Yield Strength, ksi	Ultimate Tensile Strength, ksi	% Elongation in 2 in.	Reduction in Area,%	Crack-Growth Energy (G_c), in.-lb/in.^{2}	R_c Hardness
W-24254	Annealed	none	-	128.5	170.7	7.5	53	-	34
↓	Annealed	-100°F +850°F 4 hr	H-1	291.3	302.2	3	17	58.3	54
↓	50% CW	none	-	184.0	201.6	5	50	-	39
↓	50% CW	850°F 4 hr	H-2	321.0	327.1	3	25	22.7	55.5
↓	75% CW	none	-	205.7	220.9	6	46	-	44
↓	75% CW	850°F 4 hr	H-3	298.3	308.8	2.5	13	15.7	55
↓	Welded	none	-	124.4	146.7	3.5	25	-	-
W-24254	Welded	-100°F +850°F 4 hr	H-W	245.0	252.0	1.5	5	-	-
W-24178	Annealed*	none	-	102.0	153.3	14.8	62	-	30.5
↓	Annealed*	900°F 3 hr	I-1	283.0	294.0	8	38	552.0	53.5
↓	50% CW	none	-	167.7	189.0	3.5	51	-	36.5
W-24178	50% CW	900°F 3 hr	I-3	323.8	328.4	1.5	28	220.0	55
477	50% CW	none	-	169.3	196.9	6.5	40	-	38.5
477	50% CW	900°F 3 hr	I-5	278.0	280.7	2	8	435.0	55.0
448	Annealed	none	-	105.3	150.3	10	45	-	30.5
↓	Annealed	900°F 3 hr	I-6	255.4	265.9	5	9	634.0	52
↓	50% CW	none	-	175.5	199.8	4.5	47.5	-	38
448	50% CW	900°F 3 hr	I-7	331.0	332.5	1.5	7	525.0	55
476	Annealed	none	-	128.3	174.7	5.5	48	-	36
↓	Annealed	900°F 3 hr	I-8	323.3	330.0	2.5	27	402.0	56
↓	50% CW	none	-	192.2	217.0	2.5	40	-	41
476	50% CW	900°F 3 hr	I-9	354.4	354.9	1	1.5	156.5	58
3960502	Annealed	none	-	119.5	143.5	7	55	-	29.5
↓	Annealed	900°F 3 hr	I-4	249.9	254.7	4	37	670.0	50.5
↓	50% CW	none	-	166.2	182.9	5.5	58.5	-	35.5
↓	50% CW	900°F 3 hr	I-2	302.5	308.1	4	26	321.0	52.5
↓	Welded	none	-	124.5	145.0	4.5	47	-	-
3960502	Welded	900°F 3 hr	I-W	236.6	242.0	2	20	-	-

*Material received in the 50% cold-worked condition and annealed at 1500°F in the laboratory.

TABLE 3

CHEMICAL ANALYSIS AND MECHANICAL PROPERTIES OF 6Al-4V TITANIUM

	Chemical Analysis,* %								
	C	Al	V	O_2	N_2	H_2	Ti	Fe	Other
Aerojet analysis	0.3	6.1	4.1	0.083	0.014	80 ppm	Bal	0.16	0.18

	Mechanical Properties (Transverse)			
	Yield Strength (0.2% Offset) psi	Ultimate Strength psi	Elongation %	R_c Hardness
Annealed				
Mill report	131,900	141,400	12	33.5
Aerojet test	138,000	143,800	14	34
Notched tensile strength**	--	128,500	-	-
1675°F 1 hour, W.Q. aged 900°F 8 hour				
Aerojet test	162,700	176,800	7	38.5
Notched tensile strength	--	132,000	-	-
Welded				
Aerojet test	131,500***	135,200	9.5	33.0

*Titanium Metals Corporation HT 4141.

**Using as-fatigue-cracked sample of Figure 3.

***Tensile failures in parent metal.

TABLE 4

TAP-WATER ANALYSIS

Analysis of Dissolved Solids	Parts per Million	Hypothetical Combinations of Dissolved Solids	Parts per Million	Other Characteristics	Determinations
Silica	13.8	Silica	13.8	Specific conductance, micromhos/cm	355
Aluminum oxide	Trace	Aluminum oxide	Trace	Hydrogen-ion concentration, pH	7.7
Iron oxide	Trace	Iron oxide	Trace	Boron (B), ppm	None
Calcium	56.1	Calcium bicarbonate	226.9	Fluoride (F), ppm	0.2
Magnesium	10.7	Calcium sulfate	None	Langelier index	ND*
Sodium	15.4	Calcium chloride	None	Turbidity	None
Sulfate	14.0	Magnesium bicarbonate	64.4	Color	10
Chloride	8.0	Magnesium sulfate	None	Odor	None
Carbonate	None	Magnesium chloride	None	Taste	ND*
Bicarbonate	231.9	Sodium bicarbonate	10.1	Suspended matter	None
Nitrate	1.8	Sodium carbonate	None		
Nitrate	ND*	Sodium sulfate	20.6		
Borate	None	Sodium chloride	13.4		
		Sodium nitrate	2.5		
		Sodium nitrite	ND*		
Total solids	351.7	Total solids	351.7		
Total non-volatile solids	233.8	Total hardness as $CaCO_3$	184		

*ND, not detected.

TABLE 5

AERATED DISTILLED WATER, BENT-BEAM TEST RESULTS*

Material	Variable	Code No. **	Yield Strength ksi	Failure Ratio ***	Failure Time, hrs Mean	Failure Time, hrs Range
6Al-4V titanium	Annealed	G-1	138.0	0/3	-	NF1700
6Al-4V titanium	Quenched & aged	G-2	163.0	0/3	-	NF1700
6Al-4V titanium	As welded	G-W	135.0	0/2	-	NF750
20%-Ni maraging steel	Annealed & aged	H-1	291.3	3/3	11	10.2-18
↓	50% CW & aged	H-2	321.0	1/3	330	330-NF1000
↓	75% CW & aged	H-3	293.3	2/3	2200	1284-NF3100
20%-Ni maraging steel	Welded & aged	H-W	245.0	2/3	35	23-NF70
18%-Ni maraging steel	Annealed & aged	I-4	249.9	3/3	68	60-85
↓	↓	I-6	255.4	0/3	-	NF1200
↓	↓	I-1	283.0	3/3	34.5	20.5-46.5
↓	Annealed & aged	I-8	323.2	3/3	24	20-27.5
↓	50% CW & aged	I-5	278.0	0/3	-	NF1200
↓	↓	I-2	302.5	0/3	-	NF400
↓	↓	I-7	331.0	0/3	-	NF1200
↓	↓	I-3	323.0	4/4	625	440-988
↓	50% CW & aged	I-9	354.4	1/3	668	668-NF1200
18%-Ni maraging steel	Welded & aged	I-W	236.6	0/0	-	-

*All samples were stressed to give a maximum outer-fiber stress of 75% of the 0.2%-offset yield strength.

**Code defined in Table 1.

***Ratio of number failed to number tested.

TABLE 6

AERATED TAP WATER, BENT-BEAM TEST RESULTS*

Material	Variable	Code No. **	Yield Strength ksi	Failure Ratio ***	Failure Time, hr. Mean	Failure Time, hr. Range
6Al-4V titanium	Annealed	G-1	138.0	0/3	-	NF1700
6Al-4V titanium	Quenched & aged	G-2	163.0	0/3	-	NF1700
6Al-4V titanium	As welded	G-W	135.0	0/2	-	NF750
20%-Ni maraging steel	Annealed & aged	H-1	291.3	0/3	-	NF3100
↓	50% CW & aged	H-2	321.0	0/3	-	NF1000
↓	75% CW & aged	H-3	298.3	2/3	1955	1510-NF3100
20%-Ni maraging steel	Welded & aged	H-W	245.0	3/3	5.2	3.3-6.5
18%-Ni maraging steel	Annealed & aged	I-4	249.9	0/3	-	NF500
↓	Annealed & aged	I-1	283.0	2/3	350	325-NF2000
↓	50% CW & aged	I-2	302.5	0/3	-	NF400
↓	50% CW & aged	I-3	323.0	0/3	-	NF2000
18%-Ni maraging steel	Welded & aged	I-W	236.6	0/0	-	-

*All samples were stressed to give a maximum outer-fiber stress of 75% of the 0.2%-offset yield strength.

**Code defined in Table 1.

***Ratio of number failed to number tested.

TABLE 7

AERATED SALT WATER, BENT-BEAM TEST RESULTS*

Material	Variable	Code No. **	Yield Strength ksi	Failure Ratio ***	Failure Time, hr Mean	Failure Time, hr Range
6Al-4V titanium	Annealed	G-1	138.0	0/3	-	NF1700
6Al-4V titanium	Quenched & aged	G-2	163.0	0/3	-	NF1700
6Al-4V titanium	As welded	G-W	135.0	0/2	-	NF750
20%-Ni maraging steel	Annealed & aged	H-1	291.3	3/3	7.3	6-8.5
	50% CW & aged	H-2	321.0	0/3	-	NF1000
	75% CW & aged	H-3	298.3	0/3	-	NF3100
20%-Ni maraging steel	Welded & aged	H-W	245.0	3/3	0.8	0.75-0.85
18%-Ni maraging steel	Annealed & aged	I-4	249.9	3/3	430	140-700
		I-6	255.4	0/2	-	NF1200
		I-1	283.0	3/3	51.5	19-100
	Annealed & aged	I-8	323.2	2/2	6.5	6-7
	50% CW & aged	I-5	278.0	0/2	-	NF1200
		I-2	302.5	0/3	-	NF400
		I-7	331.0	0/2	-	NF1200
		I-3	323.0	2/3	1290	1000-NF2000
	50% CW & aged	I-9	254.4	2/2	20	20-20
18%-Ni maraging steel	Welded & aged	I-W	236.6	0/0	-	-

*All samples were stressed to give a maximum outer-fiber stress of 75% of the 0.2%-offset yield strength.

**Code defined in Table 1

***Ratio of number failed to number tested.

TABLE 8

AERATED 0.25% SODIUM DICHROMATE, BENT-BEAM TEST RESULTS*

Material	Variable	Code No.**	Yield Strength ksi	Failure Ratio ***	Failure Time, hours Mean	Range
6Al-4V titanium	Annealed	G-1	138.0	0/3	-	NF1700
6Al-4V titanium	Quenched & aged	G-2	163.0	0/3	-	NF1700
6Al-4V titanium	As welded	G-W	135.0	0/2	-	NF750
20%-Ni maraging steel	Annealed & aged	H-1	291.3	1/3	1.0	1-NF3100
↓	50% CW & aged	H-2	321.0	0/3	-	NF1000
↓	75% CW & aged	H-3	298.3	0/3	-	NF3100
20%-Ni maraging steel	Welded & aged	H-W	245.0	0/3	-	NF70
18%-Ni maraging steel	Annealed & aged	I-4	249.9	0/3	-	NF500
↓	Annealed & aged	I-1	283.0	3/3	117	100-150
↓	50% CW & aged	I-2	302.5	0/3	-	NF400
↓	50% CW & aged	I-3	323.0	0/3	-	NF2000
18%-Ni maraging steel	Welded & aged	I-W	236.6	0/0	-	-

*All samples were stressed to give a maximum outer-fiber stress of 75% of the 0.2%-offset yield strength.

**Code defined in Table 1.

***Ratio of number failed to number tested.

TABLE 9

4%-SOLUBLE-OIL SOLUTION, BENT-BEAM TEST RESULTS*

Material	Variable	Code No. **	Yield Strength ksi	Failure Ratio ***	Failure Time, hr Mean	Failure Time, hr Range
6Al-4V titanium	Annealed	G-1	138.0	0/3	-	NF1700
6Al-4V titanium	Quenched & aged	G-2	163.0	0/3	-	NF1700
6Al-4V titanium	As welded	G-W	135.0	0/2	-	NF750
20%-Ni maraging steel	Annealed & aged	H-1	291.3	0/2	-	NF2000
↓	50% CW & aged	H-2	321.0	0/3	-	NF1000
↓	75% CW & aged	H-3	298.8	0/3	-	NF2000
20%-Ni maraging steel	Welded & aged	H-W	245.0	0/3	-	NF70
18%-Ni maraging steel	Annealed & aged	I-4	249.9	0/3	-	NF500
↓	Annealed & aged	I-1	283.0	3/3	417	400-450
↓	50% CW & aged	I-2	302.5	0/3	-	NF400
↓	50% CW & aged	I-3	323.0	0/3	-	NF2000
18%-Ni maraging steel	Welded & aged	I-W	236.6	0/0	-	-

*All samples were stressed to give a maximum outer-fiber stress of 75% of the 0.2%-offset yield strength.

**Code defined in Table 1.

***Ratio of number failed to number tested.

TABLE 10

140°F SATURATED AIR, BENT-BEAM TEST RESULTS*

Material	Variable	Code No. **	Yield Strength ksi	Failure Ratio ***	Failure Time, hr Mean	Failure Time, hr Range
6Al-4V titanium	Annealed	G-1	138.0	0/3	-	NF1700
6Al-4V titanium	Quenched & aged	G-2	163.0	0/3	-	NF1700
6Al-4V titanium	As welded	G-W	135.0	0/2	-	NF750
20%-Ni maraging steel	Annealed & aged	H-1	291.3	3/3	100	22-174
↓	50% CW & aged	H-2	321.0	0/3	-	NF1000
↓	75% CW & aged	H-3	298.3	3/3	1200	1080-1860
20%-Ni maraging steel	Welded & aged	H-W	245.0	3/3	10	1-14
18%-Ni maraging steel	Annealed & aged	I-4	249.9	3/3	370	170-475
↓	↓	I-6	255.4	3/3	280	212-362
↓	↓	I-1	283.0	3/3	21	20.5-21.5
↓	Annealed & aged	I-8	323.2	3/3	56.5	25.5-72
↓	50% CW & aged	I-5	278.0	0/3	-	NF1200
↓	↓	I-2	302.5	1/3	380	380-NF400
↓	↓	I-7	331.0	0/3	-	NF1200
↓	↓	I-3	323.0	3/3	260	245-290
↓	50% CW & aged	I-9	354.4	3/3	833	560-1010
18%-Ni maraging steel	Welded & aged	I-W	236.6	0/0	-	-

*All samples were stressed to give a maximum outer-fiber stress of 75% of the 0.2%-offset yield strength.

**Code defined in Table 1.

***Ratio of number failed to number tested.

TABLE 11

TRICHLOROETHYLENE IMMERSION, BENT-BEAM TEST RESULTS*

Material	Variable	Code No. **	Yield Strength ksi	Failure Ratio ***	Failure Time, hr Mean	Failure Time, hr Range
6Al-4V-titanium	Annealed	G-1	138.0	0/3	-	NF675
6Al-4V titanium	Quenched & aged	G-2	163.0	0/3	-	NF675
6Al-4V titanium	As welded	G-W	135.0	0/2	-	NF675
20%-Ni maraging steel	Annealed & aged	H-1	291.3	1/3	500	500-NF675
↓	50% CW & aged	H-2	321.0	0/3	-	NF675
↓	75% CW & aged	H-3	293.3	0/3	-	NF675
20%-Ni maraging steel	Welded & aged	H-W	245.0	3/3	48	40-68
18%-Ni maraging steel	Annealed & aged	I-1	283.0	2/3	610	550-NF675
↓	50% CW & aged	I-2	302.5	0/3	-	NF50
↓	50% CW & aged	I-3	323.0	0/3	-	NF675
18%-Ni maraging steel	Welded & aged	I-W	236.6	0/0	-	-

*All samples were stressed to give maximum outer-fiber stress of 75% of the 0.2%-offset yield strength.

**Code defined in Table 1.

***Ratio of number failed to number tested.

TABLE 12

COSMOLINE IMMERSION, BENT-BEAM TEST RESULTS*

Material	Variable	Code No. **	Yield Strength ksi	Failure Ratio ***	Failure Time, hr Mean	Failure Time, hr Range
6Al-4V titanium	Annealed	G-1	138.0	0/3	-	NF1700
6Al-4V titanium	Quenched	G-2	163.0	0/3	-	NF1700
6Al-4V titanium	As welded	G-W	135.0	0/2	-	NF750
20%-Ni maraging steel	Annealed & aged	H-11	291.3	0/3	-	NF2000
↓	50% CW & aged	H-2	321.0	0/3	-	NF1000
↓	75% CW & aged	H-3	293.3	0/3	-	NF2000
20%-Ni maraging steel	Welded & aged	H-W	245.0	0/0	-	-
18%-Ni maraging steel	Annealed & aged	I-4	249.9	0/3	-	NF500
↓	Annealed & aged	I-1	283.0	0/3	-	NF2000
↓	50% CW & aged	I-3	323.0	0/0	-	NF2000
18%-Ni maraging steel	Welded & aged	I-W	236.6	0/0	-	-

*All samples were stressed to give maximum outer-fiber stress of 75% of the 0.2%-offset yield strength.

**Code defined in Table 1.

***Ratio of number failed to number tested.

TABLE 13

LABORATORY AIR, BENT-BEAM TEST RESULTS*

Material	Variable	Code No. **	Yield Strength ksi	Failure Ratio ***	Failure Time hr Mean	Failure Time hr Range
6Al-4V titanium	Annealed	G-1	138.0	0/0	-	-
6Al-4V titanium	Quenched & aged	G-2	163.0	0/0	-	-
6Al-4V titanium	As welded	G-W	135.0	0/2	-	NF750
20%-Ni maraging steel	Annealed & aged	H-1	291.3	0/3	-	NF3100
↓	50% CW & aged	H-2	321.0	0/2	-	NF1000
↓	75% CW & aged	H-3	293.3	0/3	-	NF3100
20%-Ni maraging steel	Welded & aged	H-W	245.0	0/0	-	-
18%-Ni maraging steel	Annealed & aged	I-4	249.9	0/0	-	-
↓	↓	I-6	255.4	0/2	-	NF1200
↓	↓	I-1	283.0	0/3	-	NF2000
↓	Annealed & aged	I-8	323.2	0/1	-	NF1200
↓	50% CW & aged	I-5	278.0	0/1	-	NF1200
↓	↓	I-2	302.5	0/0	-	-
↓	↓	I-7	331.0	0/2	-	NF1200
↓	↓	I-3	323.0	0/3	-	NF2000
↓	50% CW & aged	I-9	354.4	0/2	-	NF1200
18%-Ni maraging steel	Welded & aged	I-W	336.6	0/0	-	-

*All samples were stressed to give a maximum outer-fiber stress of 75% of the 0.2%-offset yield strength.

**Code defined in Table 1.

***Ratio of number failed to number tested.

TABLE 14

SEACOAST EXPOSURE, BENT-BEAM TEST RESULTS*

Material	Variable	Code No.**	Yield Strength ksi	Failure Ratio***	Failure Time, hr Mean	Failure Time, hr Range
6Al-4V titanium	Annealed	G-1	138.0	0/3	-	NF980
6Al-4V titanium	Quenched & aged	G-2	163.0	0/3	-	NF980
6Al-4V titanium	As welded	G-W	135.0	0/2	-	NF980
20%-Ni maraging steel	Annealed & aged	H-1	291.3	3/3	140	116-188
	50% CW & aged	H-2	321.0	1/3	800	800-NF980
	75% CW & aged	H-3	293.3	1/3	860	860-NF980
20%-Ni maraging steel	Welded & aged	H-W	245.0	0/0	-	-
18%-Ni maraging steel	Annealed & aged	I-6	255.4	0/2	-	NF980
	Annealed & aged	I-1	283.0	6/6	380	312-450
	Annealed & aged	I-8	323.2	1/2	350	350-NF980
	50% CW & aged	I-5	278.0	0/2	-	NF980
		I-2	302.5	0/0	-	-
		I-7	331.0	0/2	-	NF980
		I-3	323.0	0/3	-	NF980
	50% CW & aged	I-9	354.4	0/2	-	NF980
18%-Ni maraging steel	Welded & aged	I-W	236.6	0/0	-	-

*All samples were stressed to give a maximum outer-fiber stress of 75% of the 0.2%-offset yield strength.

**Code defined in Table 1.

***Ratio of number failed to number tested.

TABLE 15

DISTILLED WATER, CENTER-NOTCH TESTS*

Material	Variable	Code No.**	K_c ksi $\sqrt{in.}$	Failure Ratio***	Failure Time, hr Mean	Failure Time, hr Range
6Al-4V titanium	Annealed	G-1	85.0	0/3	-	NF100
6Al-4V titanium	Quenched & aged	G-2	86.2	0/3	-	NF100
20%-Ni maraging steel	Annealed & aged	H-1	39.3	3/3	5.1	4.6-6.6
20%-Ni maraging steel	50% CW & aged	H-2	24.5	0/0	-	-
20%-Ni maraging steel	75% CW & aged	H-3	20.5	1/3	121	121-NF300
18%-Ni maraging steel	Annealed & aged	I-4	133.0	2/2	62.4	51.4-73.3
	Annealed & aged	I-6	129.5	0/1	-	NF200
	Annealed & aged	I-1	121.0	3/3	85.3	83-87
	Annealed & aged	I-8	103.2	0/0	-	-
	50% CW & aged	I-5	107.2	0/1	-	NF200
		I-2	92.2	0/0	-	-
		I-7	119.0	0/0	-	-
		I-3	76.4	2/2	13.2	12.6-13.8
18%-Ni maraging steel	50% CW & aged	I-9	64.4	0/0	-	-

*All samples were given a direct load of 75% of K_c.

**Code defined in Table 1.

***Ratio of number failed to number tested.

TABLE 16

3%-SODIUM-CHLORIDE SOLUTION, CENTER-NOTCH TESTS*

Material	Variable	Code No. **	K_c ksi$\sqrt{in.}$	Failure Ratio ***	Failure Time, hours Mean	Range
6Al-4V titanium	Annealed	G-1	85.0	0/2	-	NF100
6Al-4V titanium	Quenched & aged	G-2	86.2	0/2	-	NF100
20%-Ni maraging steel (Test at 83% of K_c)	Annealed & aged	H-1	39.3	1/1	4.2	-
20%-Ni maraging steel	↓	H-1	39.3	2/2	7.2	6.6-7.8
20%-Ni maraging steel (Test at 60% of K_c)	↓	H-1	39.3	1/1	8.2	-
20%-Ni maraging steel (Test at 27% of K_c)	Annealed & aged	H-1	39.3	1/1	12.7	-
20%-Ni maraging steel	50% CW & aged	H-2	24.5	2/2	14.0	8-20
20%-Ni maraging steel	75% CW & aged	H-3	20.5	2/2	40.2	34.4-46
18%-Ni maraging steel	Annealed & aged	I-4	133.0	2/2	12.5	9.5-15.6
↓	↓	I-6	129.5	3/3	22	10-35
↓	↓	I-1	121.0	2/2	20.6	18-23
↓	Annealed & aged	I-8	103.2	2/2	8.8	8.3-9.3
↓	50% CW & aged	I-5	107.2	2/2	13.4	12.5-14.2
↓	↓	I-2	92.2	0/0	-	-
↓	↓	I-7	119.0	3/3	9.9	4.4-12.9
↓	↓	I-3	76.4	2/2	5.9	5.0-6.9
18%-Ni maraging steel	50% CW & aged	I-9	64.4	2/2	4.5	4.0-5.0

*All samples were given a direct load of 75% of K_c except as noted.

**Code defined in Table 1.

***Ratio of number failed to number tested.

TABLE 17

0.25% SODIUM DICHROMATE, CENTER-NOTCH TESTS*

Material	Variable	Code No. **	K_c ksi$\sqrt{in.}$	Failure Ratio ***	Failure Time hours Mean	Failure Time hours Range
6Al-4V titanium	Annealed	G-1	85.0	0/2	-	NF100
6Al-4V titanium	Quenched & aged	G-2	86.2	0/2	-	NF100
20%-Ni maraging steel	Annealed & aged	H-1	39.3	0/2	-	NF200
20%-Ni maraging steel	50% CW & aged	H-2	24.5	0/0	-	-
20%-Ni maraging steel	75% CW & aged	H-3	20.5	0/2	-	NF100
18%-Ni maraging steel	Annealed & aged	I-4	133.0	0/0	-	-
↓	Annealed & aged	I-1	121.0	1/1	67.9	-
↓	50% CW & aged	I-5	107.2	0/1	-	NF200
↓	↓	I-2	92.2	0/0	-	-
↓	↓	I-7	119.0	0/2	-	NF100
18%-Ni maraging steel	50% CW & aged	I-3	76.4	1/1	33.2	-

*All samples were given a direct load of 75% of K_c.

**Code defined in Table 1.

***Ratio of number failed to number tested.

TABLE 18

4%-SOLUBLE-OIL SOLUTION, CENTER-NOTCH TESTS*

Material	Variable	Code No. **	K_c ksi$\sqrt{\text{in.}}$	Failure Ratio ***	Failure Time, hours Mean	Range
6Al-4V titanium	Annealed	G-1	85.0	0/1	-	NF100
6Al-4V titanium	Quenched & aged	G-2	86.2	0/1	-	NF100
20%-Ni maraging steel	Annealed & aged	H-1	39.3	0/2	-	NF200
20%-Ni maraging steel	Annealed & aged	H-2	24.5	0/0	-	-
20%-Ni maraging steel	75% CW & aged	H-3	20.5	0/1	-	NF100
18%-Ni maraging steel	Annealed & aged	I-4	133.0	0/0	-	-
↓	Annealed & aged	I-1	121.0	0/0	-	-
↓	50% CW & aged	I-2	92.2	0/0	-	-
18%-Ni maraging steel	50% CW & aged	I-3	76.4	0/0	-	-

*All samples were given a direct load of 75% of K_c.

**Code defined in Table 1.

***Ratio of number failed to number tested.

TABLE 19

EVALUATION OF PROTECTIVE COATINGS ON H-11 STEEL
(FOR PREVENTION OF STRESS-CORROSION CRACKING)

Surface Condition	Coating	Aerated 3% NaCl Solution: Failure Ratio*	Aerated 3% NaCl Solution: Failure Time, hr Mean	Aerated 3% NaCl Solution: Failure Time, hr Range	140°F Saturated Air: Failure Ratio*	140°F Saturated Air: Failure Time, hr Mean	140°F Saturated Air: Failure Time, hr Range	Seacoast Exposure: Failure Ratio*	Seacoast Exposure: Failure Time, hr Mean	Seacoast Exposure: Failure Time, hr Range
Surface ground or sanded	None (control)	4/4	1.6	0.8-2.5	2/2	64	48-70	2/2	116	116-116
	Polyurethane	3/3**	149	144-168	6/6**	3500	2830-5500	1/2	250	250-NF 900
	Inhibited epoxy 454-1-1	0/2	-	NF 1200	3/3**	2720	2590-2850	0/2	-	NF 900
	Inhibited epoxy 463-1-5	0/3	-	NF 3100	3/3	656	400-976	0/2	-	NF 900
	Inhibited epoxy 463-4-8	3/3	550	525-578	3/3	845	289-1512	-	-	-
	Epoxy 463-1-5 over 454-1-1	0/4**	-	NF 5860	4/4**	4000	2590-4950	-	-	-
	Zinc silicate, Type 4	2/2	1.2	0.8-1.6	2/2	422	147-696	1/2	116	116-NF 900
	80% aluminum epoxy	2/2	1.00	100-100	2/2	30	16-45	2/2	660	550-780
	70% titanium epoxy	2/2	150	140-160	2/2	198	136-256	1/2	720	720-NF 900
Sand-blasted	None (control)	2/2	18.5	14-23	1/1	26.5	-	1/1	188	-
	Pure vinyl	0/2	-	NF 1500	1/2	670	670-NF 1500	0/2	-	NF 900
	Zinc silicate, Type 4	2/2	14	10-18	0/2	-	NF 1500	0/2	-	NF 900
	Epoxy over zinc silicate, Type 4	2/2	77	1.5-153	2/2	513	422-504	0/1	-	NF 900
	Inorganic zinc, Type 11	2/2	687	674-702	2/2	821	723-819	0/4	-	NF 900
	Epoxy 188 over inorganic zinc 11	2/2	54	42-56	0/2	-	NF 2160	-	-	-
	Organic zinc XL-4-245	2/2	214	27-400	2/2	766	742-790	-	-	-
	Modified vinyl system	2/2	550	520-583	2/2	640	435-850	1/2	450	450-NF 900

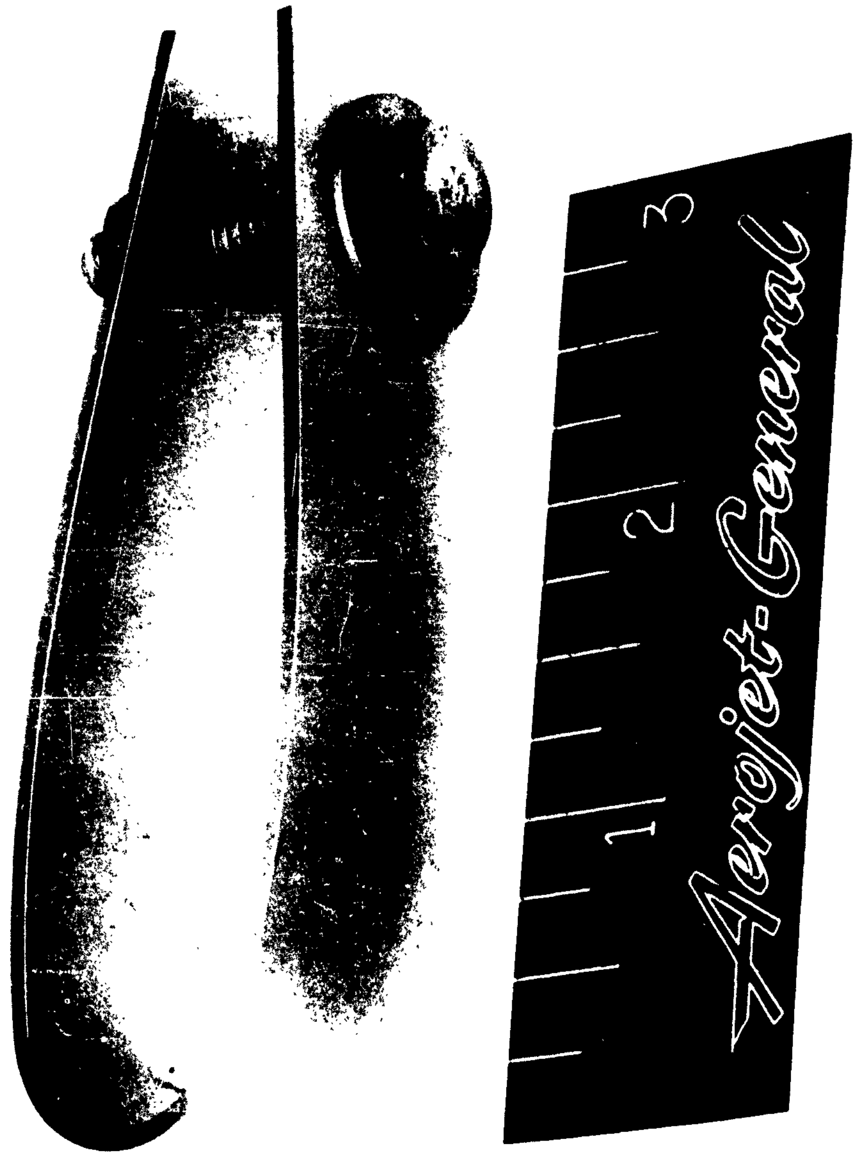
*Ratio of number failed to number exposed.

**Data taken from earlier work; samples not in current testing.

1062-615

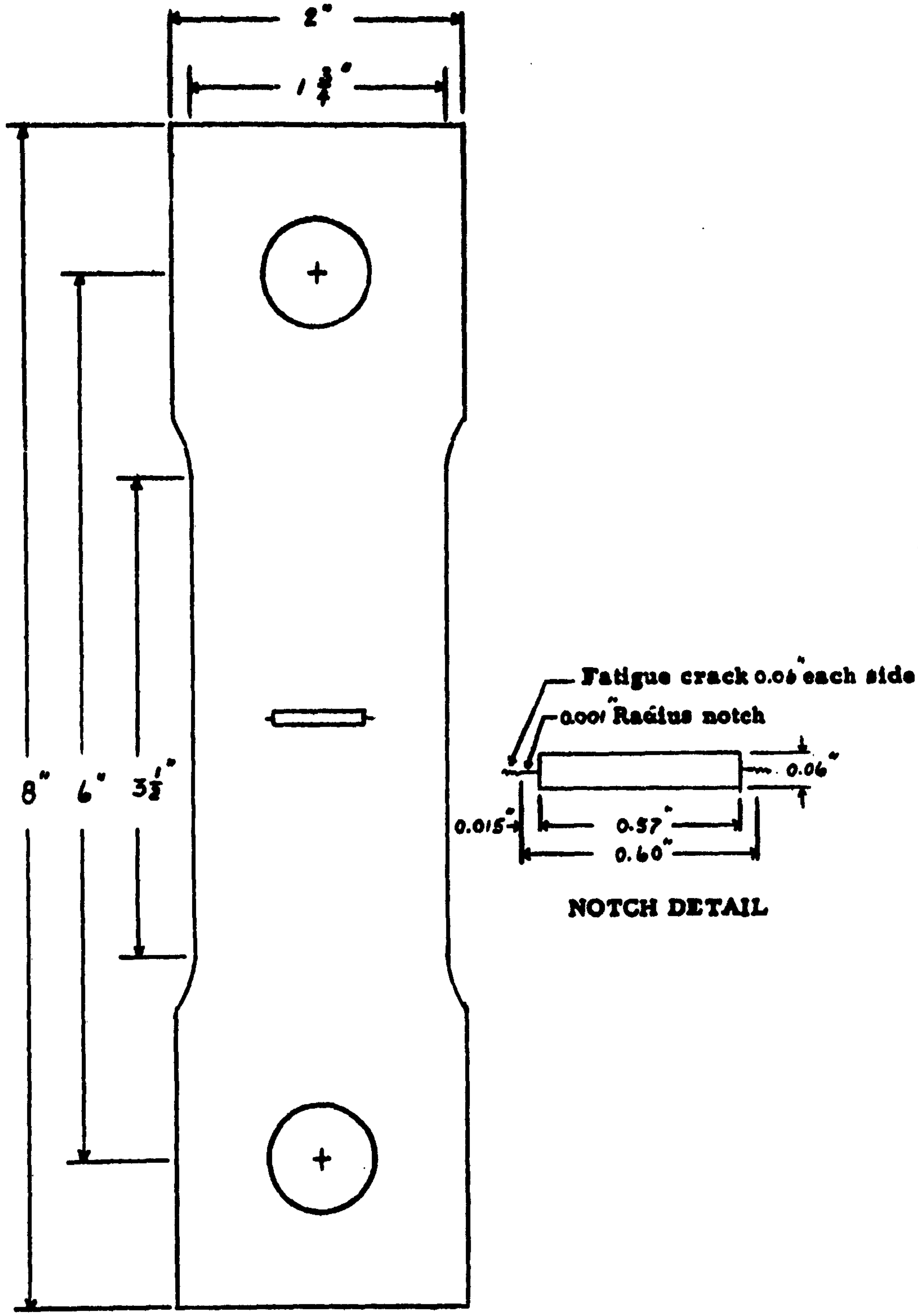
Insulated Phelps Bent-Beam Specimens

Figure 1



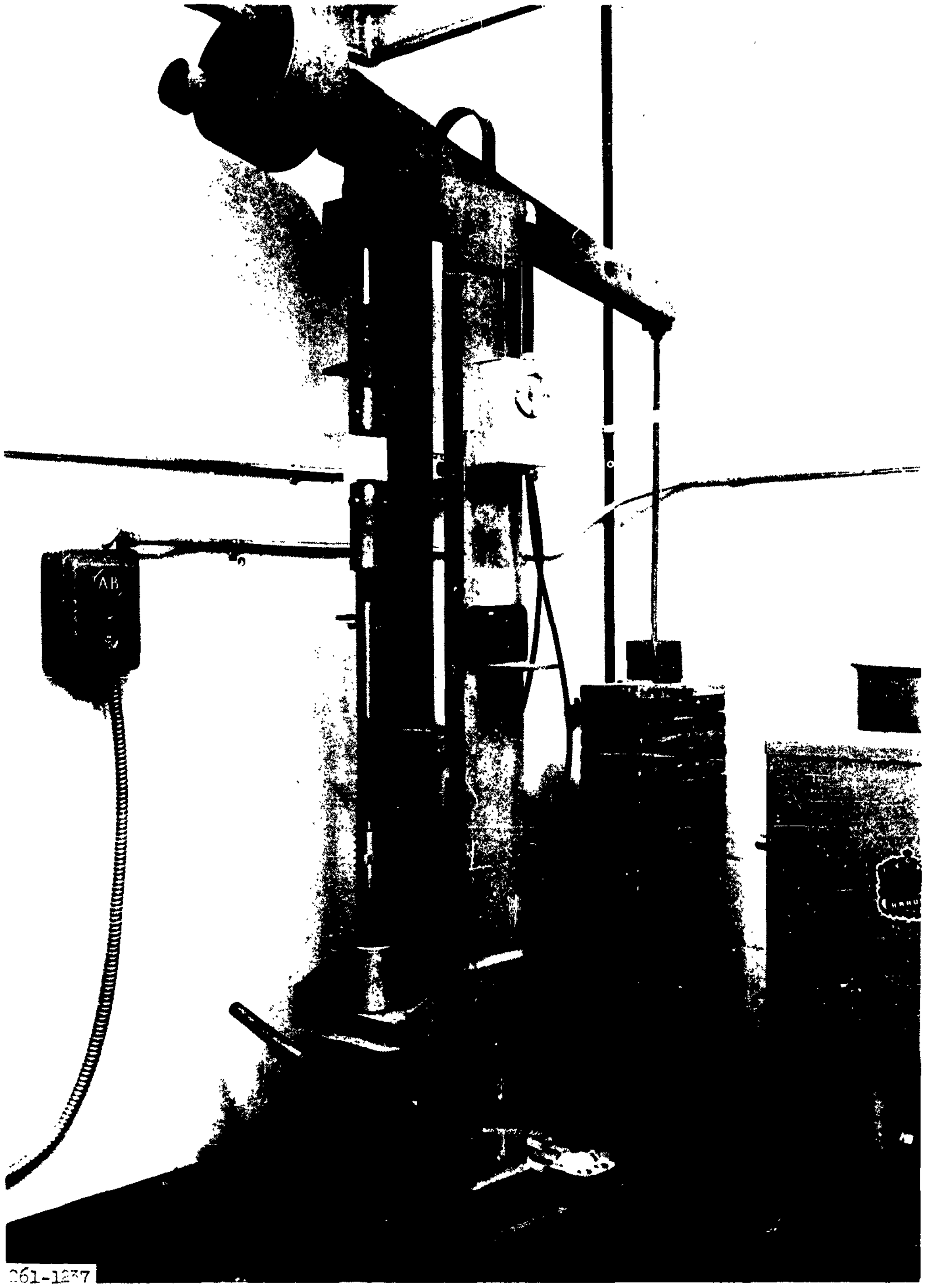
U-Bend Test Specimen

Figure 2



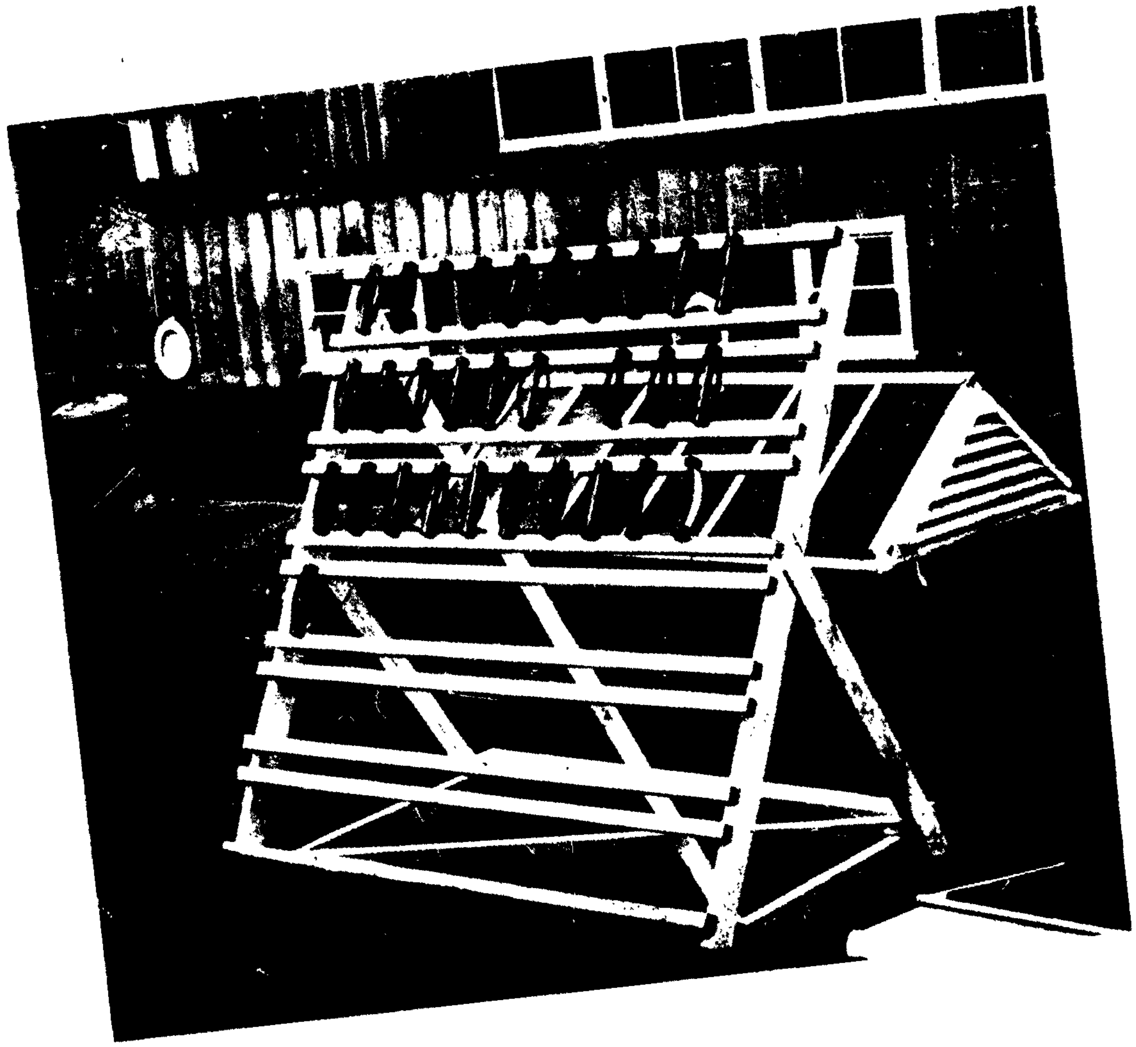
ELOX-NOTCHED SPECIMEN

Figure 3



Stress-Corrosion Test Setup for Center-Notched Specimens

Figure 4



Seacoast-Exposure Test Rack

Figure 5

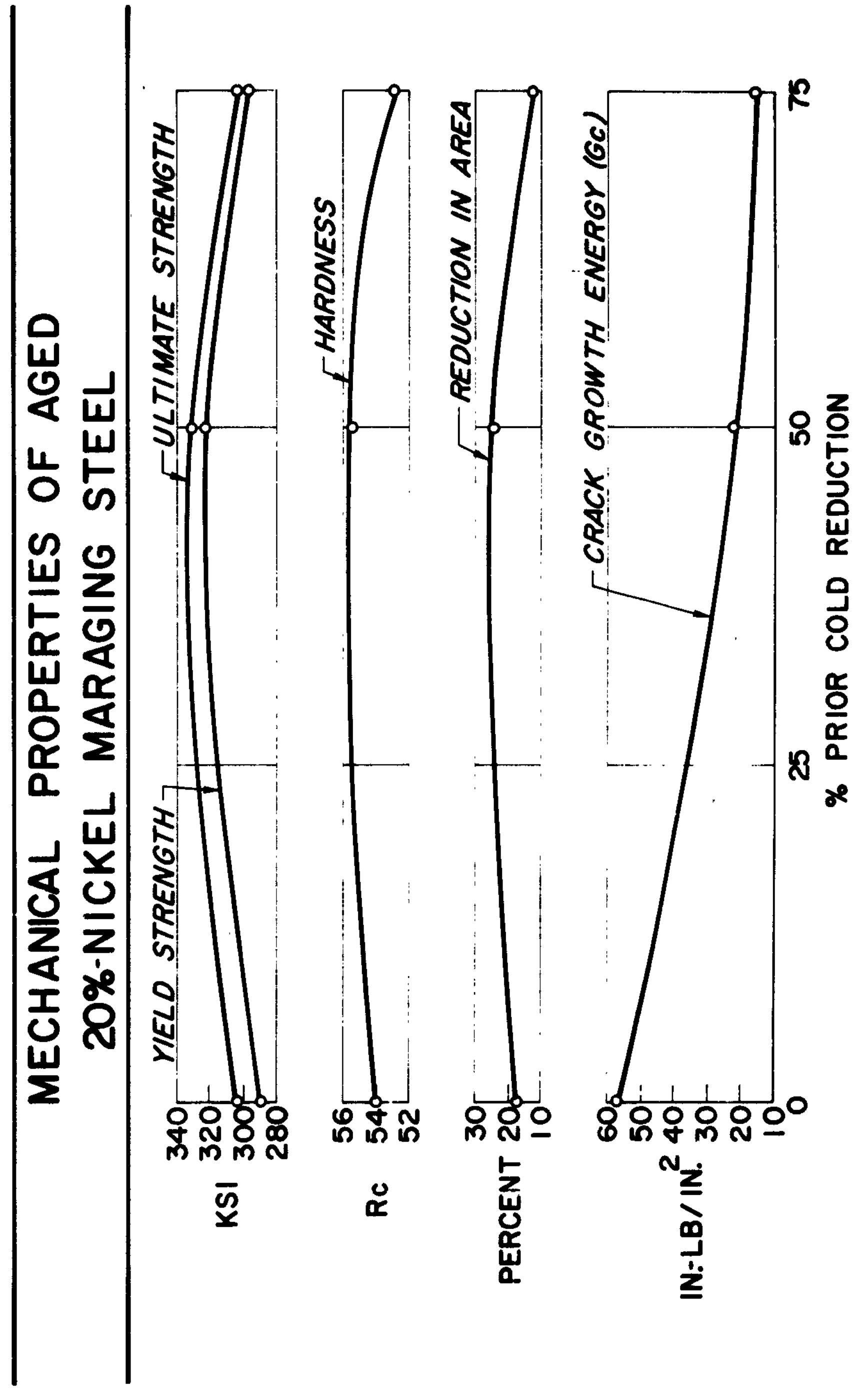

MECHANICAL PROPERTIES OF AGED
20%-NICKEL MARAGING STEEL
KSI
340
320
300
280
YIELD STRENGTH
ULTIMATE STRENGTH
Rc
56
54
52
HARDNESS
PERCENT
30
20
10
REDUCTION IN AREA
IN-LB/IN.2
60
50
40
30
20
10
0
CRACK GROWTH ENERGY (Gc)
0
25
50
75
% PRIOR COLD REDUCTION

Figure 6

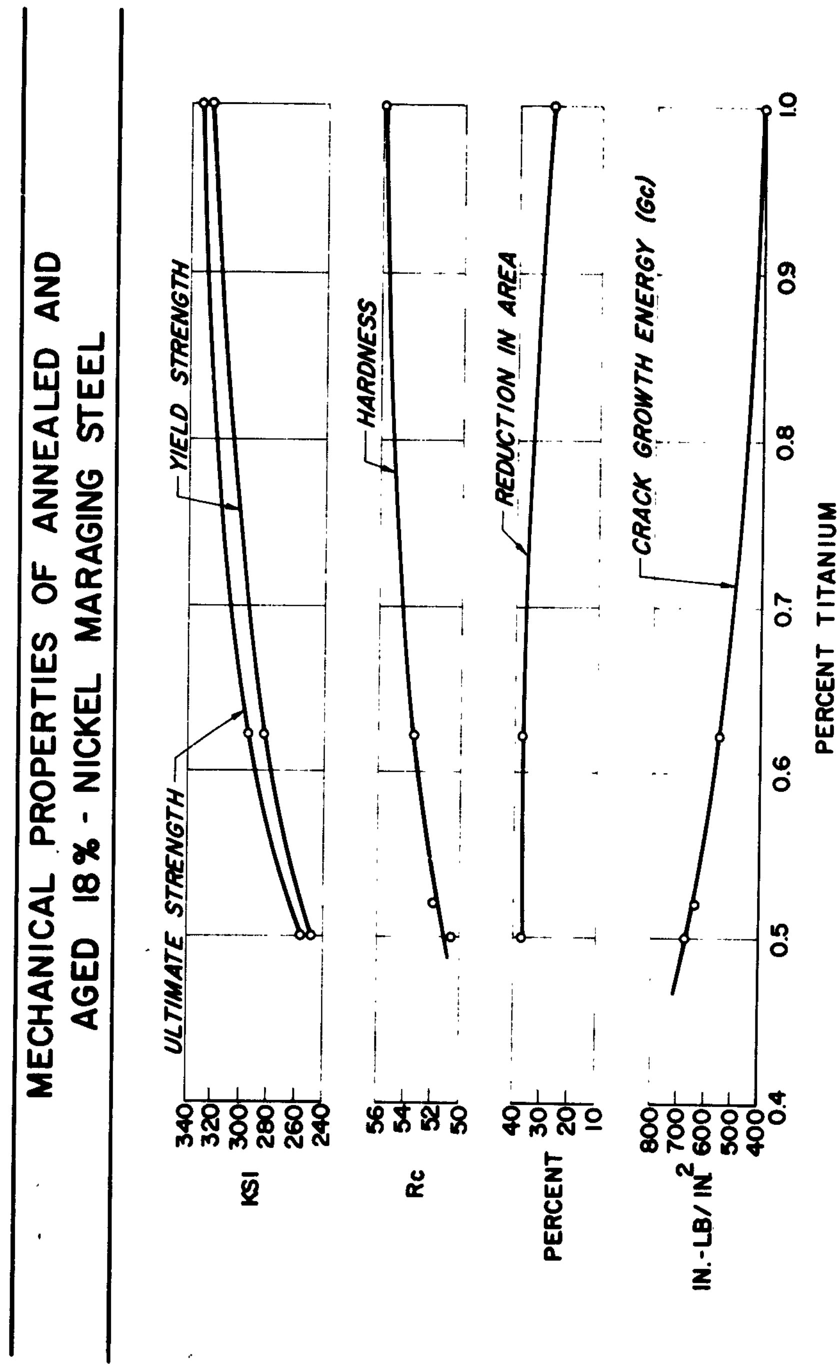

MECHANICAL PROPERTIES OF ANNEALED AND
AGED 18% - NICKEL MARAGING STEEL
ULTIMATE STRENGTH
YIELD STRENGTH
HARDNESS
REDUCTION IN AREA
CRACK GROWTH ENERGY (Gc)
KSI
340 320 300 280 260 240
Rc
56 54 52 50
PERCENT
40 30 20 10
IN.-LB/IN2
800 700 600 500 400
0.4 0.5 0.6 0.7 0.8 0.9 1.0
PERCENT TITANIUM

Figure 7

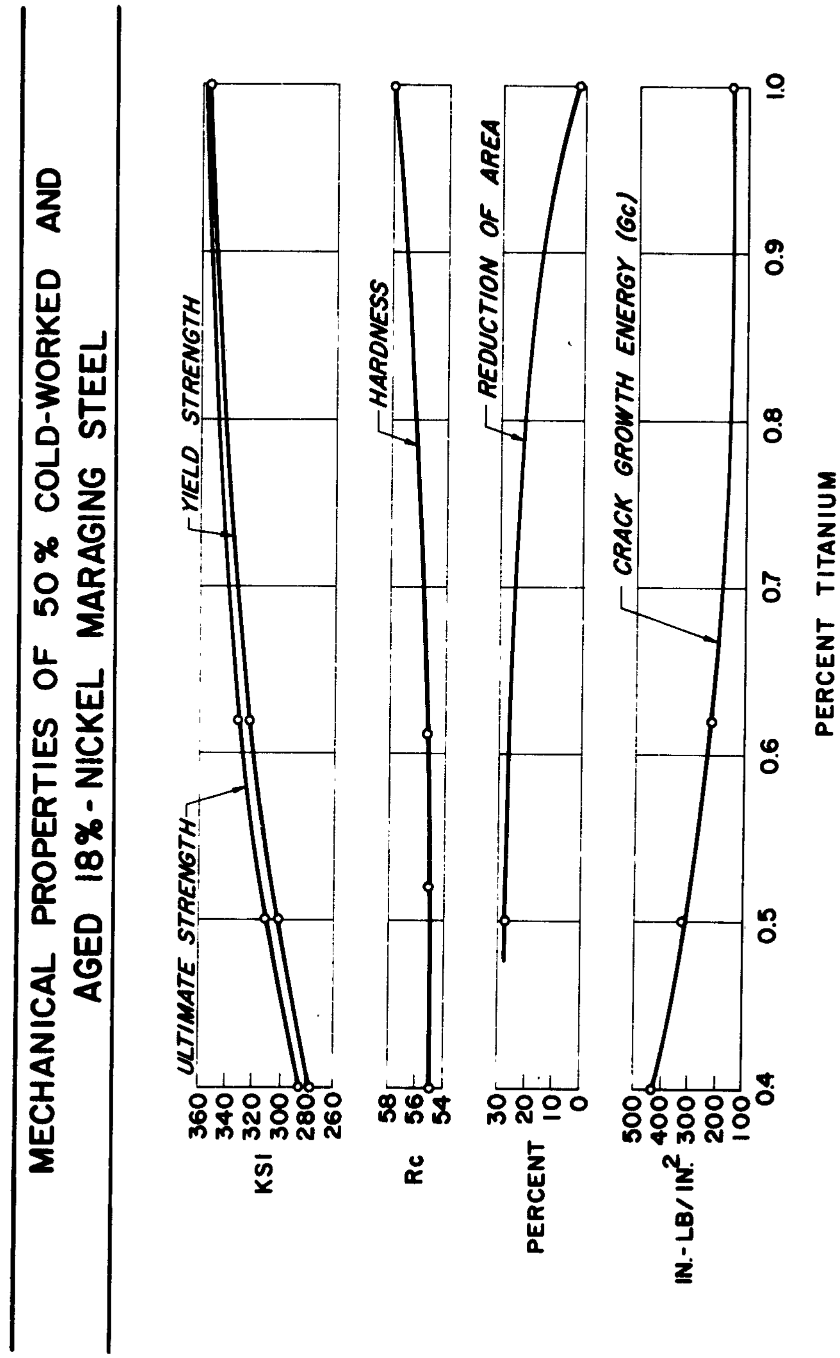
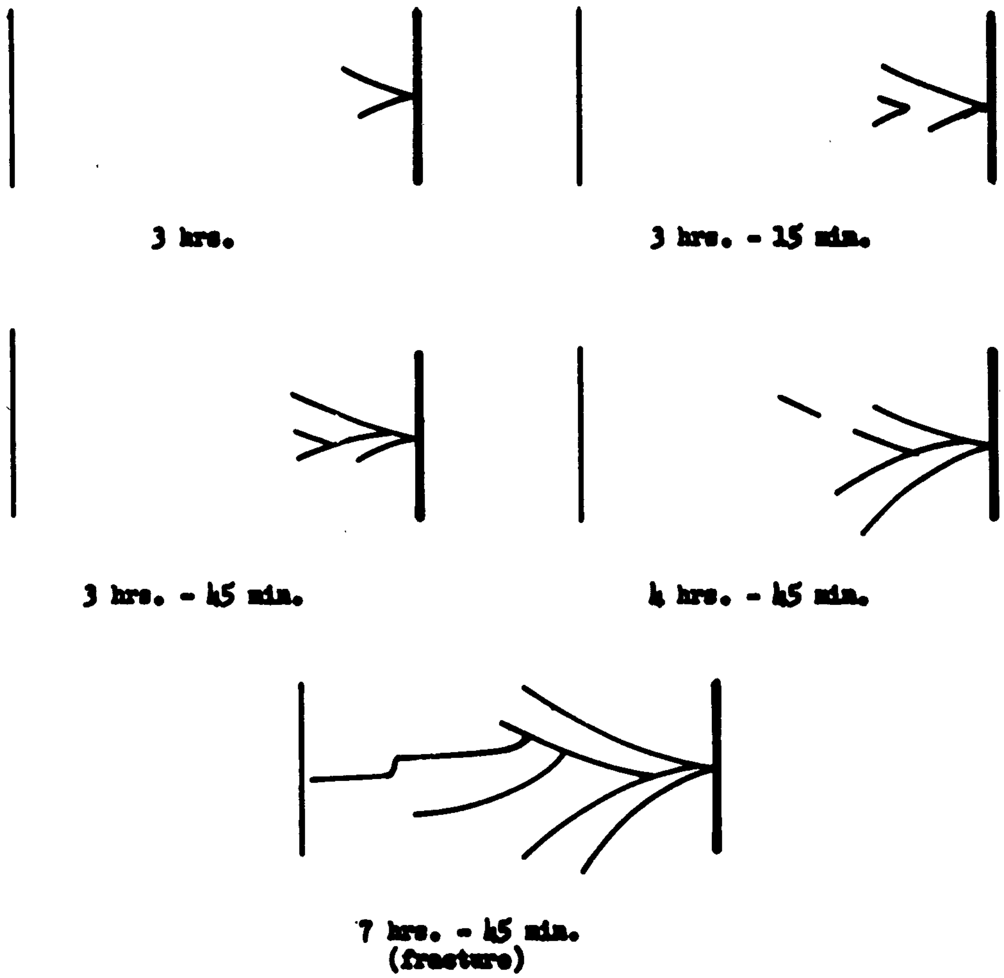
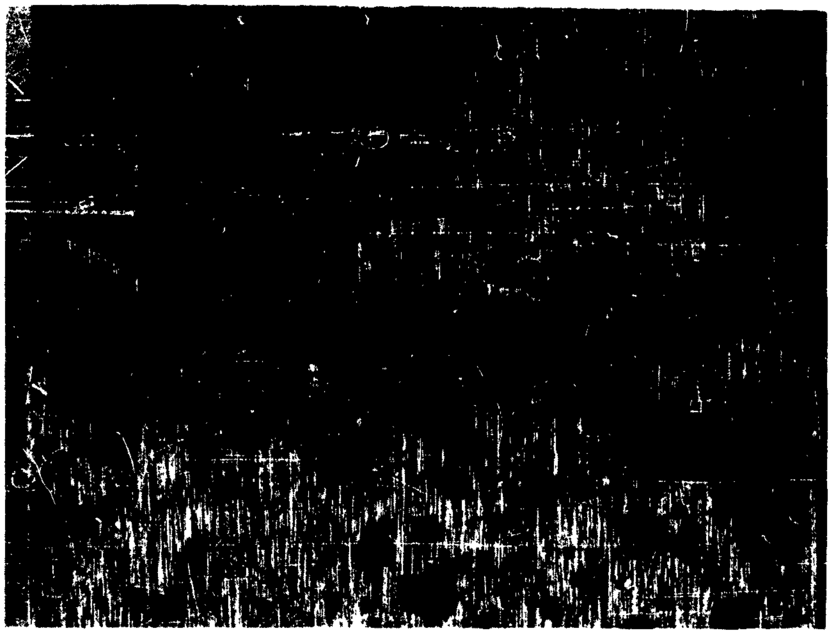

MECHANICAL PROPERTIES OF 50% COLD-WORKED AND
AGED 18%-NICKEL MARAGING STEEL
ULTIMATE STRENGTH
YIELD STRENGTH
HARDNESS
REDUCTION OF AREA
CRACK GROWTH ENERGY (Gc)
KSI
360
340
320
300
280
260
Rc
58
56
54
PERCENT
30
20
10
0
IN.-LB/IN.2
500
400
300
200
100
0.4
0.5
0.6
0.7
0.8
0.9
1.0
PERCENT TITANIUM

Figure 8



Crack Propagation Study on 20%-Nickel Maraging Steel in Salt Water

Figure 9



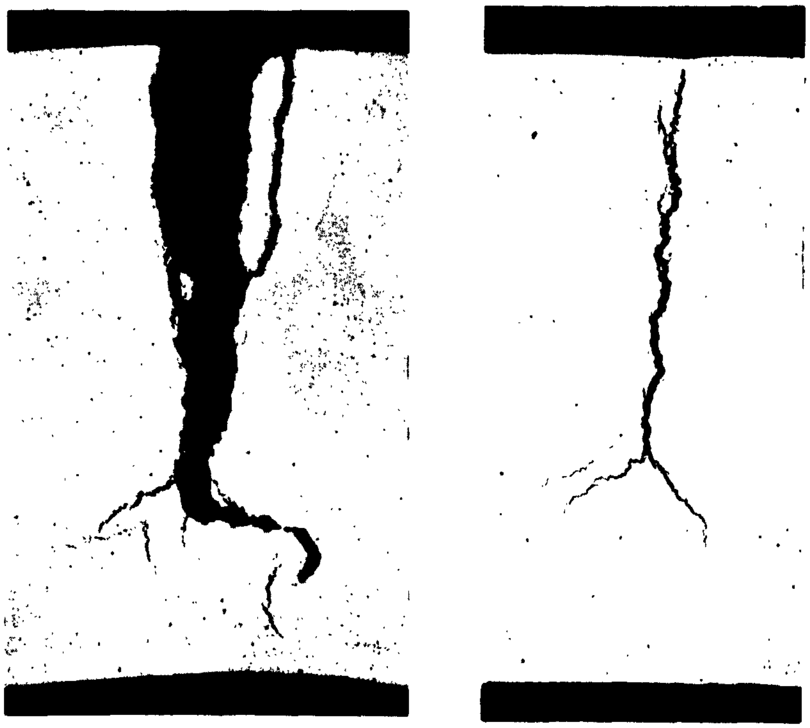
Crack Pattern on Surface of Beam Sample after 10 hours in Aerated Distilled Water. (5X)

Vertical View of Cracking in Above Sample Showing Intergranular Cracks. Etchant is Diluted Marbles Reagent (1000X)

Stress-Corrosion Crack Pattern on 20%-Nickel Maraging Steel

Figure 10

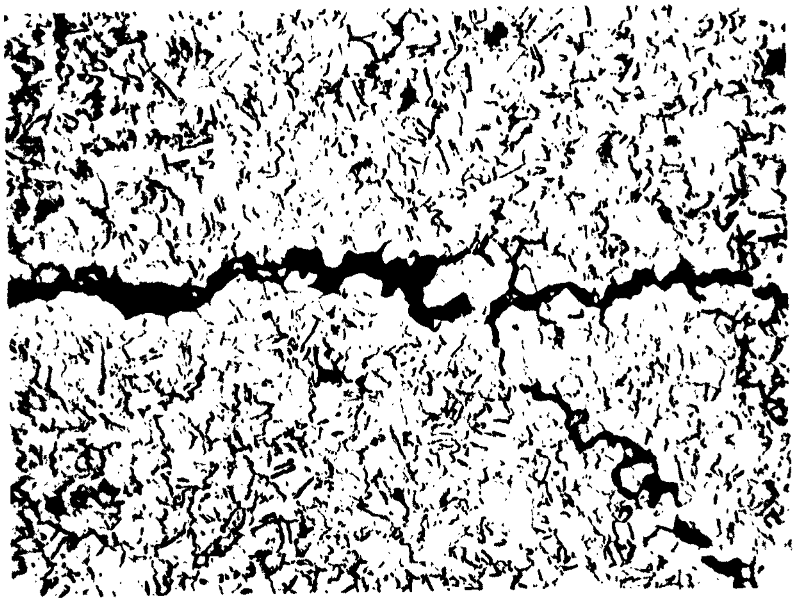
Surface of Annealed-and-Aged 18%-Nickel
Maraging Steel Cracked in Chromate
Solution (Approx. 1X)



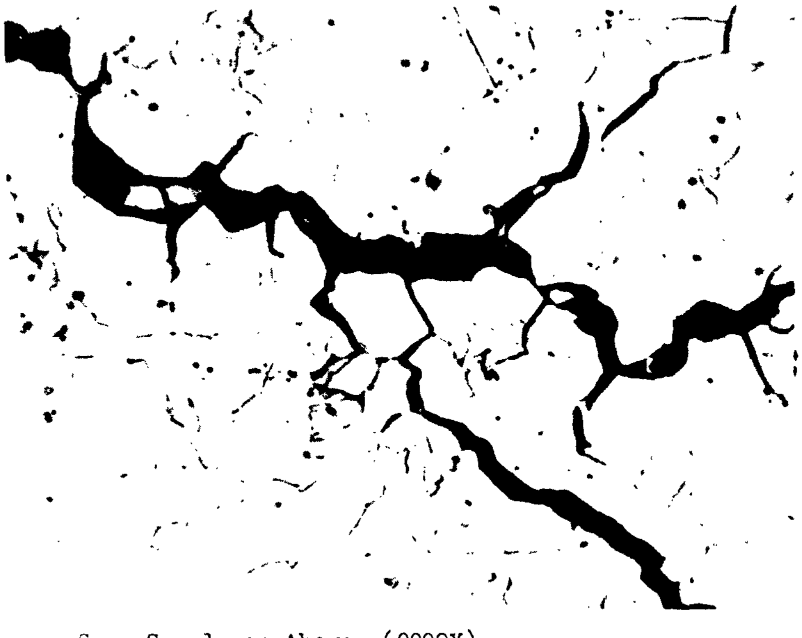
Longitudinal Section Through Cracked Area
Showing Main Crack (left) and Branch Crack
(right) (50X)

Stress-Corrosion-Crack Pattern in 18%-Nickel Maraging Steel (I-1)

Figure 11



Vertical Section of Failed Annealed-and-Aged 18%-Nickel Maraging Steel Speci.ien Showing Intergranular Cracks. Marbles Etch (250X)



Same Sample as Above (2000X)

Photomicrographs of Stress-Corrosion Cracks in 18%-Nickel Maraging Steel (I-1)

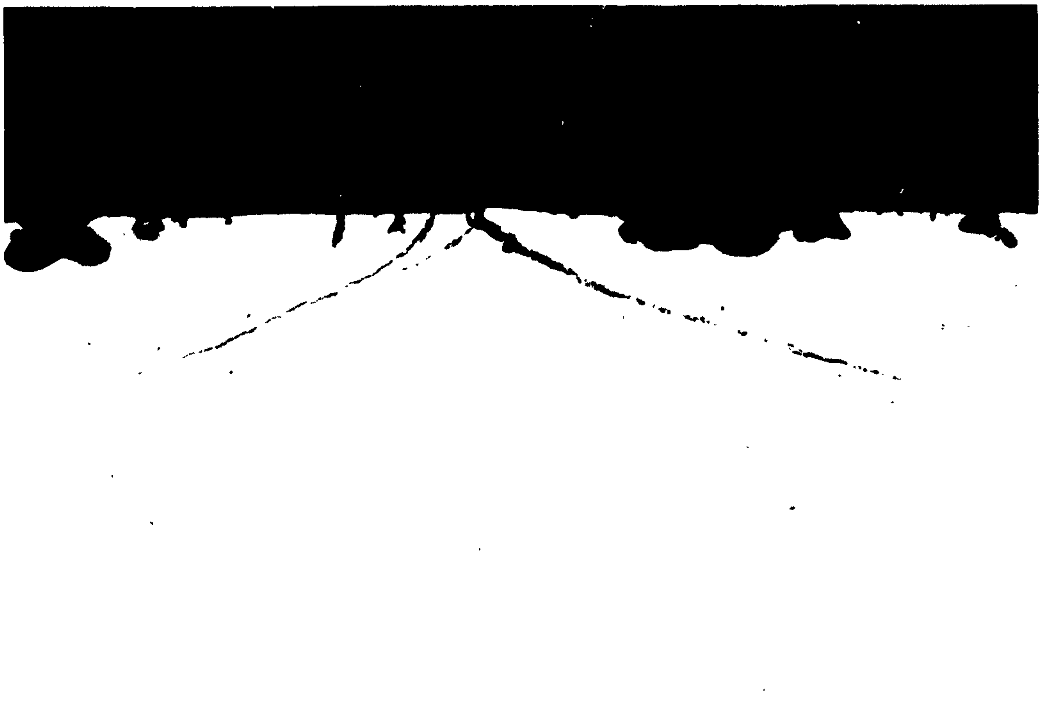
Figure 12

Surface of Cold-Worked-and-Aged 18%-Nickel Maraging Steel After 10-Days at 140°F in High Humidity Stress Corrosion Test. Surface has been Wire-Brushed. (Approx. 2X)

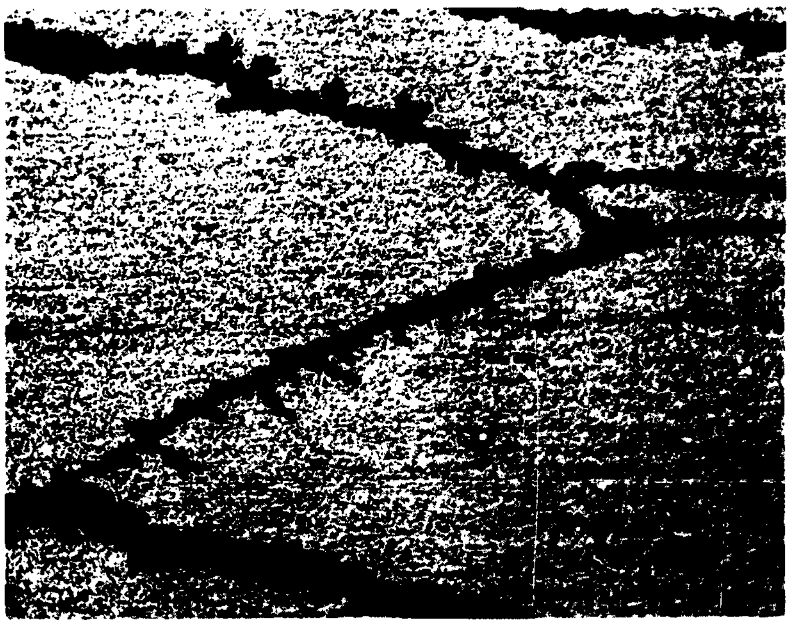
Cross-Section of Above Sample Showing Possible Cracking Along Slip Planes. (10X)

Stress-Corrosion-Crack Pattern in 18%-Nickel Maraging Steel (Group I-3)

Figure 13



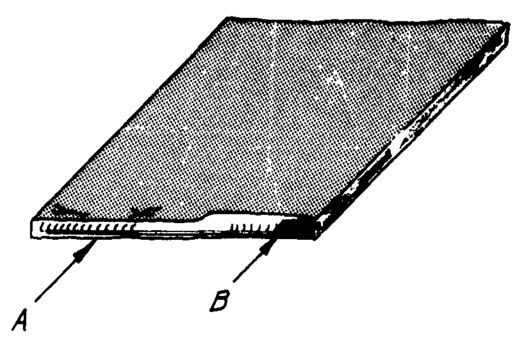
View of Surface in Lightly Cracked Area Showing Pitting Attack (100X)



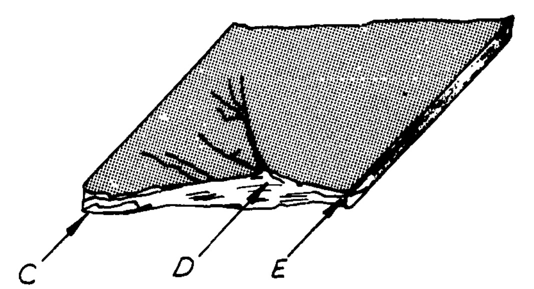
General Structure in Interior of Highly Cracked Area.
Etchant - 10% Ammonium Persulphate-electrolytic. (500X)

Photomicrographs of Stress-Corrosion Cracking in 18%-Nickel Maraging Steel (Group I-3)

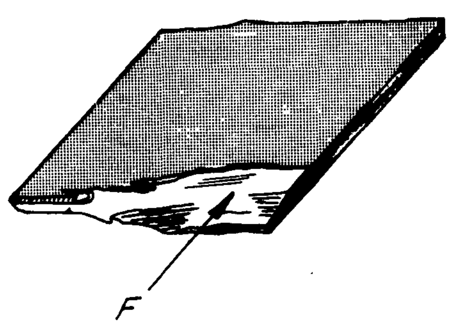
Figure 14



Uncoated H-11 Steel, Failed in 2.5 Hours in Aerated 3% Salt Water



20%-Nickel Maraging Steel (Group H-1), Failed in 1 Hour in 0.25%-Sodium-Dichromate Solution



18%-Nickel Maraging Steel (Group I-3), Failed in 626 Hours in Aerated Distilled Water

Location of Electron-Microscope Fractographs

Figure 15

Electron-Microscope Fractograph of H-11 Steel (View A, Figure 15) Showing Typical Area of Brittle Fracture, with Multiple Fracturing (17,500X)

Figure 16

Electron-Microscope Fractograph of H-11 Steel (View B, Figure 15) Showing Typical Fracture-Initiation Area, with Multiple Fracturing in Areas That May Have Microstructure Modeling Possibly Caused by Corrosion (35,000X)

Figure 17

Electron-Microscope Fractograph of 20%-Nickel Maraging Steel (View C, Figure 15) Showing Ductile-Fracture Domains, with Prominent Inclusions Along Domain Grains and Surface of Grains Showing Modeled Effect of Ductile-Adhesion Fracture (17,500X)

Figure 18

Electron-Microscope Fractograph of 20%-Nickel Maraging Steel (View D, Figure 15) Showing Brittle-Type Fracture Occurring Stepwise Along Direction of Failure, with Orientation Change to Procession of Fracture at Left (17,500X)

Figure 19

Electron-Microscope Fractograph of 20%-Nickel Maraging Steel (View E, Figure 15) Showing Intergranular-Type Fracture, with Evidence of Inclusions in Fracture Domains and Indications That Sample Failed in Tension (7000X)

Figure 20

Electron-Microscope Fractograph of 18%-Nickel Maraging Steel (View F, Figure 15) Showing Stepwise Brittle Fracture and Areas of Microcracking Along Vaguely Outlined Domains (17,500X)

Figure 21