**SLOW STRAIN RATE FRACTURE OF HIGH-STRENGTH STEEL
AT CONTROLLED ELECTROCHEMICAL POTENTIALS IN
AMMONIUM CHLORIDE, POTASSIUM CHLORIDE, AND AMMONIUM NITRATE SOLUTIONS**

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ABSTRACT

Slow strain rate testing has been undertaken to determine the effects of the individual chemical species on the fracture process of high-strength 4340 steel. Test environments included potassium chloride, ammonium nitrate, and ammonium chloride at concentrations from 0.001 to 1.0 mole per liter at ambient temperature. Tests were performed at cathodic and anodic controlled potentials, as well as at the open-circuit potential, to delineate the stress corrosion cracking range.

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Introduction

Failure analyses of cartridge-ignition starter systems of jet aircraft have identified combustion product residues as the corrosive agents responsible for pitting and eventual rupture of starter breech chambers constructed of high-strength steel [1]. Combustion product residues collected from failed breech chambers were used in a moistened condition as an environment in slow strain rate tests (SSRTs). SSRT results confirmed the susceptibility of the breech chamber steel to environmentally induced cracking [2].

SSRTs have also been performed using combustion product residues taken from used, but still serviceable, breech chambers. These tests, which were conducted at controlled electrochemical potentials, demonstrated that the corrosion potential is at the brink of the stress corrosion cracking potential range for steels in this environment [3].

X-ray diffraction analyses of residues collected from failed and used breech chambers yielded detectable amounts of ammonium chloride (NH_4Cl), potassium chloride (KCl), and ammonium nitrate (NH_4NO_3), in addition to iron oxides [2,3]. The present study was undertaken to determine the individual contributions of each of these chemical compounds to the fracture process in AISI 4340 high-strength steel in slow strain rate tensile tests. To assess the electrochemical potential effects on the fracture process, the tests were conducted at controlled

potentials. The environments consisted of solutions containing 100, 1,000, and 10,000 ppm by weight of NH_4Cl , KCl , and NH_4NO_3 . The pHs of the test solutions were adjusted to 3, 5, or 7. The tests were conducted at ambient room temperature.

Materials, Equipment, and Procedures

Steel Samples: The tensile test specimens were AISI 4340 high-strength steel heat-treated to a Rockwell C 38-42 hardness, corresponding to a tensile strength of 1,170 to 1,240 MPa (170,000 to 180,000 lb/in²). The test specimens were fabricated from 6.35-mm-diameter rod stock to a gage length of approximately 38 mm and a gage diameter of 1.5 mm in accordance with "ASTM Standard Methods for Mechanical Testing of Steel Products (A 370)." After heat treatment, the gage length of the test specimens was ground and polished to a 600-grit surface finish.

Testing Machine: The SSRTs were conducted using a universal tensile test machine with a load capacity of 20,000 lb (89,000 N). The tests were performed at a constant extension rate of 1×10^{-7} m/s (4×10^{-6} in/s), corresponding to a strain rate of approximately 2.7×10^{-6} /s.

Corrosion Test Cell: The corrosion test cell consisted of a 1-liter pyrex cylinder containing specimen holders, a graphite counter electrode, and a reference saturated calomel electrode (SCE). About 750 mL of test solution was used for each test. The solution was neither agitated nor aerated during the test. A fresh solution was used for each test. The tensile test specimen was installed in the test cell so that the entire gage length of the specimen was immersed in the solution. In the tests at controlled potentials, the specimen was polarized either anodically or cathodically using a potentiostat/galvanostat. The potential of the test specimen was controlled within plus or minus 1 mV. A digital voltmeter was used to continuously monitor the specimen potential during the SSRTs. Figure 1 is a sketch of the test apparatus and the electrical connections between the test specimen and potentiostat/galvanostat.

Test Solutions: Test solutions were prepared by adding 100, 1,000, or 10,000 mg of reagent-grade NH_4Cl , KCl , or NH_4NO_3 to distilled water to make 1 liter of test solution. These solutions are equivalent to concentrations of 100, 1,000, and 10,000 ppm by weight. The pHs of the test solutions were adjusted to the 3, 5, or 7 using hydrochloric acid (HCl) for the chloride solutions and nitric acid (HNO_3) for the nitrate solutions.

Test Procedures: After the apparatus was prepared and the steel specimen was installed, the test solution was poured into the test cell. The counter and reference electrodes were then positioned in the cell. The specimen potential was measured and, where appropriate, controlled during the course of the test. A tension load of 100 lb (450 N) was applied manually to ensure proper seating and alignment of the specimen in the test machine grips. Test data, load versus displacement, were recorded at 20-lb (89-N) increments by computer.

When the SSRT was completed, the failed specimen was immediately removed from the test cell to prevent further corrosion. It was then ultrasonically cleaned in acetone for approximately 5 minutes to remove loose corrosion products on the surface. The gage length of failed specimens showing some degree of brittleness was examined under a stereo microscope for evidence of pitting and crack initiation. Specimens were examined using a scanning electron microscope for evidence of corrosion cracking.

Embrittlement and cracking susceptibility were evaluated by comparing time-to-failure (t_f), percentage reduction in area (RA), percentage elongation (El), and ultimate tensile strength (UTS) of the specimens tested in the corrosive environments with data obtained on a specimen tested in an inert environment (vegetable oil). Normalized data for t_f , RA, and UTS were determined using ratios of the values obtained in the various solutions to the values obtained in the inert environment.

Results

SSRT results are presented in Tables I through IX. Normalized results of the specimens tested in the corrosive environments versus those tested in an inert environment (vegetable oil) are presented in Table X.

Tests in NH_4Cl : The results of the tests in NH_4Cl solutions are presented in Table I through III. Figures 2 and 3 show plots of the normalized t_f and RA versus electrode potential at various chemical concentrations.

At the controlled potential of -650 mV, there was no embrittlement at any of the three NH_4Cl concentrations or pHs; the SSRT fractures were cup-and-cone-type fractures.

At the test potential of -350 mV vs SCE, only minor reduction of t_f and RA were observed at the concentration of 1,000 ppm and pH of 5. However, the fracture of the test specimen was still ductile. No embrittlement was found in any other NH_4Cl solutions. The SSRT fractures of these tests were ductile and cup-and-cone.

The results of tests at the controlled potential of -450 mV vs SCE indicate the most severe embrittlement occurs on the specimens exposed to 1,000-ppm solution at a pH of 5. The fracture was completely brittle. There was no sign of reduction in the cross-sectional area of the test specimens. Observation along the gage length of the test specimens revealed numerous circumferential hairline secondary cracks. Similar secondary cracks were also observed on the specimens tested in the 10,000-ppm solution at the same pH. No similar cracking or embrittlement was observed on the specimens exposed to the NH_4Cl solutions at pHs of 3 and 7 at the controlled potential of 450 mV vs SCE.

The test at the corrosion potential revealed the results similar to those of the tests at the controlled potential of -350 mV vs SCE. All test specimens failed in the ductile manner. There were no serious reductions observed in t_f , RA, El, and UTS of specimens tested in solutions at pHs of 3 and 7 or in 100-ppm solution at a pH of 5. Minor reductions in the t_f , RA, and El were found in the 1,000- and 10,000-ppm solutions at a pH of 5. Secondary cracks were also observed on these test specimens; however, the failure was still substantially ductile.

The controlled potential of -850 mV vs SCE was the most severe in the entire test series. Embrittlement was observed in all test solutions and concentrations at a pH of 3. Extensive reductions in t_f and El were observed on all test specimens. The fracture was completely brittle; however, no secondary cracks were revealed on the specimen gage length. Similar results also were observed on the specimens tested at concentrations of 1,000 and 10,000 ppm at pHs of 5 and 7. Observation of the specimens tested at the concentration of 100 ppm at pHs of 5 and 7 indicated no sign of embrittlement. These specimens experienced ductile failure.

Test in KCl: Tables IV through VI show the results of the tests in the KCl solutions. Normalize time-to-failure and reduction in area as a function of electrode potential are presented in Figures 4 and 5.

The results of the tests in the three concentrations and pHs indicated that no cracking related to corrosion occurred at the anodically controlled potentials of -350 and -450 mV vs SCE, at the corrosion potential, or at the cathodically controlled potential of -650 mV. All test specimens were failed by ductile type. No evidence of stress corrosion-induced cracking was observed on the gage length of any of the test specimens.

The most significant embrittlement was found at the test potential of -850 mV vs SCE at all three KCl concentrations at a pH of 3. Similar embrittlement was observed on the specimens tested in 10,000-ppm solution at a pH of 7. The failure was completely brittle with extremely low reduction in the cross-sectional area. No embrittlement was found at test concentrations of 100 or 1,000 ppm. At a pH of 5, no serious cracking was found at all three concentrations. The typical fracture was ductile cup-and-cone. No secondary cracking was observed.

Tests in NH_4NO_3 : Tables VII through IX show the test results for the NH_4NO_3 solutions. Normalized time-to-failure and reduction in area as a function of electrochemical potential are presented in Figures 6 and 7.

There was no embrittlement at the anodically controlled potentials of -350 or -450 mV vs SCE, at the corrosion potential, or at the cathodically controlled potential of -650 mV vs SCE for all test solutions and pHs.

Embrittlement was observed on the specimens tested at all three concentrations at the cathodically controlled potential of -850 mV vs SCE at a pH of 3. Extensive reduction of the time-to-failure was observed on the test specimens. The failure exhibited rapidly propagated brittle fracture with no significant reduction in cross-sectional area. Similar embrittlement was found in the solution containing 10,000 ppm at a pH of 5 and at the same potential. The fractures were completely brittle. Embrittlement was also found at the concentration of 1,000 ppm at a pH of 5. However, the degree of severity was less in comparison to the tests at 10,000 ppm. At the neutral pH of 7, no serious embrittlement was observed in any test concentrations, and the test specimens experienced ductile failure.

Discussion

The embrittlement observed in these solutions at the electrochemical potential of -850 mV vs SCE must be caused by hydrogen embrittlement. There was no appearance of corrosion on the surface of any of the steel specimens tested at this potential. The embrittlement occurs in the NH_4Cl , KCl , and NH_4NO_3 solutions at a pH of 3. At a pH of 5, embrittlement occurred at the high concentrations, but not at the low concentrations. At a pH of 7, embrittlement occurred only in the NH_4Cl and KCl solutions at the high concentrations, but not in the NH_4NO_3 solutions, even at the highest concentration of 10,000 ppm.

A potential of -650 mV vs SCE, which is slightly cathodic to the corrosion potential in all three solutions, appears to prevent embrittlement in the SSRT. Anodic polarization to -450 and -350 mV promotes general corrosion to the steel, but not necessarily embrittlement. Severe embrittlement occurs only in the NH_4Cl solution at the intermediate concentration of 1,000 ppm and a pH of 5. This is stress corrosion cracking (SCC). At a more active potential (-350 mV), the general dissolution rate must be high enough to blunt incipient cracks. A similar argument can be made for the lesser embrittlement at the highest NH_4Cl concentration. The increased aggressiveness of the environment promotes general corrosion and tends to blunt stress concentrations. If the presence of secondary cracking is an indicator, the electrochemical potential range for SCC in NH_4Cl extends from about the corrosion potential (-613 to -623 mV) to about -350 mV at a pH of 5. No stress corrosion cracking was observed on other test solutions.

The lack of sensitivity of UTS to the failure mode can be partly explained by the ratio of high yield strength to tensile strength in the steel, but it also indicates that crack initiation does not occur until after some substantial uniform elongation has occurred. In addition, observation of the normalized plots in Figures 1 to 6 shows that time-to-failure is not as sensitive indicators of embrittlement as is percentage reduction in area.

Conclusions

1. Of the three compounds studied using SSRT at controlled electrochemical potentials, only NH_4Cl caused stress corrosion cracking in the high strength 4340 steel when tested at a pH of 5. The corrosion potential of about -620 mV vs. SCE is at the brink of the potential range for SCC. The most severe stress corrosion cracking was observed at -450 mV and at the intermediate solution concentration of 1,000 ppm NH_4Cl .
2. Hydrogen induced cracking was observed at -850 mV in all test solutions at a pH of 3. At a pH of 5, hydrogen embrittlement occurred in the NH_4Cl and NH_4NO_3 solutions, but not in the KCl solutions and only at high concentrations. At a pH of 7, embrittlement was found in NH_4Cl and KCl solutions at high concentrations, but no similar brittleness was observed in NH_4NO_3 solutions.
3. The test results reveals that reduction of specimen cross-sectional area and time-to-failure are very sensitive to the corrosion cracking susceptibility. Inversely, there is no significant reduction of ultimate tensile strength and elongation on the specimens susceptible to corrosion cracking in comparison to those tested in an inert environment, if crack initiation and propagation occurred only at a high stress level of approximate tensile strength.

References

1. Perkins, P. C., Daniels, R. D., and Gillies, A. B., "Failure Analyses of Steel Breech Chambers Used With Aircraft Cartridge-Ignition Starters," Analyzing Failures, V. S. Goel, Ed., American Society for Metals, Metals Park, OH, 1986, pp. 143-150.
2. Kennelley, K. J. and Daniels, R. D., "Stress Corrosion Cracking of 4340 Steel in Aircraft Ignition Starter Residues," Journal of Materials Engineering, Vol. 9, No. 1, 1987, pp. 35-40.
3. Daniels, R. D., Sadarangani, A. P., Magner, M. P., and Kennelley, K. J., "Effects of Electrochemical Potential on the Slow Strain Rate Fracture of 4340 Steel in a Combustion Product Residue," Environmentally Assisted Cracking: Science and Engineering, ASTM STP 1049, W. B. Lisagor, T.W. Crooker, and B. N. Leis, Eds., American Society for Testing and Materials, Philadelphia, 1990, pp. 103-116.

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TABLE I

Slow Strain Rate Tests on 4340 High Strength SteelExposed to NH₄Cl Solutions at pH of 3, Room Temperature.Strain Rate of 2.7×10^{-6} /s

Conc ^a ppm	E ^b mV vs SCE	t _f ^c hrs	El ^d %	RA ^e %	UTS ^f MPa	Fracture
Test in Vegetable Oil		8.20	24	55	1275	Ductile
10,000 ppm						
	-350	6.63	20	50	1197	Ductile
	-450	6.63	20	51	1251	Ductile
	-560 (Ecor)	7.39	27	55	1229	Ductile
	-650	8.04	23	55	1163	Ductile
	-850	3.32	10	1	1236	Brittle
1,000 ppm						
	-350	6.76	20	51	1165	Ductile
	-450	7.29	22	51	1207	Ductile
	-615 (Ecor)	7.83	24	54	1273	Ductile
	-650	6.16	19	51	1207	Ductile
	-850	3.41	10	1	1185	Brittle
100 ppm						
	-350	8.02	24	53	1267	Ductile
	-450	8.08	24	54	1273	Ductile
	-620 (Ecor)	7.51	22	53	1185	Ductile
	-650	7.80	24	55	1207	Ductile
	-850	2.11	6	2	1141	Brittle

^a Conc = test solution concentrations.^b E = controlled potential; Ecor = corrosion potential measured versus SCE.^c t_f = time to failure.^d El = elongation of test specimen based on 1.5-in gage length.^e RA = reduction of test specimen cross-section area.^f UTS = ultimate tensile strength of test specimen.

TABLE II

Slow Strain Rate Tests on 4340 High Strength SteelExposed to NH₄Cl Solutions at pH of 5, Room Temperature.Strain Rate of 2.7×10^{-6} /s

Conc ^a ppm	E ^b mV vs SCE	t _f ^c hrs	El ^d %	RA ^e %	UTS ^f MPa	Fracture
Test in Vegetable Oil						
		7.80	36	60	1207	Ductile
10,000 ppm						
-350		6.40	26	44	1125	Ductile
-450		7.76	31	46	1230	Cracks
-613 (Ecor)		7.76	31	43	1225	Cracks
-650		7.62	34	55	1189	Ductile
-850		5.53	21	0	1043	Brittle
1,000 ppm						
-350		5.56	23	47	1110	Cracks
-450		4.49	19	0	1065	Brittle
						cracks
-621 (Ecor)		7.63	31	30	1227	Cracks
-650		7.44	29	56	1172	Ductile
-850		4.94	20	0	1103	Brittle
100 ppm						
-350		7.86	30	52	1210	Ductile
-450		7.41	31	58	1186	Ductile
-623 (Ecor)		8.10	32	56	1227	Ductile
-650		7.80	30	58	1172	Ductile
-850		6.84	24	35	1158	Cracks

^a Conc = test solution concentrations.^b E = controlled potential; Ecor = corrosion potential measured versus SCE.^c t_f = time to failure.^d El = elongation of test specimen based on 1.5-in gage length.^e RA = reduction of test specimen cross-section area.^f UTS = ultimate tensile strength of test specimen.

TABLE III

Slow Strain Rate Tests on 4340 High Strength SteelExposed to NH₄Cl Solutions at pH of 7, Room Temperature,Strain Rate of 2.7×10^{-6} /s

Conc ^a ppm	E ^b mV vs SCE	t _f ^c hrs	El ^d %	RA ^e %	UTS ^f MPa	Fracture
Test in Vegetable Oil		8.20	24	55	1275	Ductile
10,000 ppm						
	-350	6.50	19	51	1207	Ductile
	-450	6.73	21	51	1229	Ductile
	-627 (Ecor)	7.71	23	55	1295	Ductile
	-650	7.72	21	54	1207	Ductile
	-850	6.31	18	16	1119	Partially & brittle
1,000 ppm						
	-350	7.63	23	54	1251	Ductile
	-450	8.41	25	53	1273	Ductile
	-628 (Ecor)	8.14	25	55	1295	Ductile
	-650	8.21	25	53	1295	Ductile
	-850	6.84	16	24	1163	Partially & brittle
100 ppm						
	-350	6.80	21	51	1207	Ductile
	-450	6.96	21	52	1251	Ductile
	-634 (Ecor)	8.14	25	55	1295	Ductile
	-650	8.34	22	54	1273	Ductile
	-850	7.30	22	55	1185	Ductile

^a Conc = test solution concentrations.^b E = controlled potential; Ecor = corrosion potential measured versus SCE.^c t_f = time to failure.^d El = elongation of test specimen based on 1.5-in gage length.^e RA = reduction of test specimen cross-section area.^f UTS = ultimate tensile strength of test specimen.

TABLE IV

Slow Strain Rate Tests on 4340 High Strength SteelExposed to KCl Solutions at pH of 3, Room Temperature.Strain Rate of 2.7×10^{-6} /s

Conc ^a ppm	E ^b mV vs SCE	t _f ^c hrs	El ^d %	RA ^e %	UTS ^f MPa	Fracture
Test in Vegetable Oil						
		8.20	24	55	1275	Ductile
10,000 ppm						
	-350	5.70	17	47	1124	Ductile
	-450	7.52	22	52	1213	Ductile
	-533 (Ecor)	7.80	22	55	1200	Ductile
	-650	7.70	22	54	1227	Ductile
	-850	4.77	14	1	1186	Brittle
1,000 ppm						
	-350	7.53	22	50	1229	Ductile
	-450	7.02	20	52	1211	Ductile
	-548 (Ecor)	7.34	21	51	1159	Ductile
	-650	7.70	22	53	1185	Ductile
	-850	2.77	9	1	1164	Brittle
100 ppm						
	-350	8.01	23	53	1141	Ductile
	-450	8.13	24	55	1229	Ductile
	-553 (Ecor)	8.10	24	54	1164	Ductile
	-650	7.67	22	51	1185	Ductile
	-850	1.56	5	1	1097	Brittle

^a Conc = test solution concentrations.^b E = controlled potential; Ecor = corrosion potential measured versus SCE.^c t_f = time to failure.^d El = elongation of test specimen based on 1.5-in gage length.^e RA = reduction of test specimen cross-section area.^f UTS = ultimate tensile strength of test specimen.

TABLE V

Slow Strain Rate Tests on 4340 High Strength SteelExposed to KCl Solutions at pH of 5, Room Temperature.Strain Rate of 2.7×10^{-6} /s

Conc ^a ppm	E ^b mV vs SCE	t _f ^c hrs	El ^d %	RA ^e %	UTS ^f MPa	Fracture
Test in Vegetable Oil						
		7.80	36	60	1207	Ductile
10,000 ppm						
	-350	7.27	29	50	1116	Ductile
	-450	7.79	31	55	1172	Ductile
	-573 (Ecor)	8.20	33	58	1220	Ductile
	-650	7.71	31	56	1213	Ductile
	-850	7.50	29	54	1179	Ductile
1,000 ppm						
	-350	7.30	29	51	1158	Ductile
	-450	7.65	31	55	1193	Ductile
	-585 (Ecor)	8.20	34	56	1225	Ductile
	-650	7.62	31	55	1202	Ductile
	-850	7.90	30	56	1197	Ductile
100 ppm						
	-350	7.95	32	52	1172	Ductile
	-450	7.32	29	57	1185	Ductile
	-597 (Ecor)	7.61	33	56	1230	Ductile
	-650	7.61	31	58	1224	Ductile
	-850	7.27	29	56	1185	Ductile

^a Conc = test solution concentrations.^b E = controlled potential; Ecor = corrosion potential measured versus SCE.^c t_f = time to failure.^d El = elongation of test specimen based on 1.5-in gage length.^e RA = reduction of test specimen cross-section area.^f UTS = ultimate tensile strength of test specimen.

TABLE VI

Slow Strain Rate Tests on 4340 High Strength SteelExposed to KCl Solutions at pH of 7, Room Temperature.Strain Rate of 2.7×10^{-6} /s

Conc ^a ppm	E ^b mV vs SCE	t _f ^c hrs	El ^d %	RA ^e %	UTS ^f MPa	Fracture
Test in Vegetable Oil		8.20	24	55	1275	Ductile
10,000 ppm						
	-350	7.50	20	50	1186	Ductile
	-450	7.15	21	52	1248	Ductile
	-608 (Ecor)	8.30	24	55	1386	Ductile
	-650	7.45	18	46	1110	Ductile
	-850	4.47	13	4	965	Brittle
1,000 ppm						
	-350	7.41	22	51	1207	Ductile
	-450	7.81	24	55	1290	Ductile
	-612 (Ecor)	7.68	23	55	1273	Ductile
	-650	7.91	23	53	1295	Ductile
	-850	7.61	22	54	1273	Ductile
100 ppm						
	-350	7.48	22	52	1295	Ductile
	-450	8.13	24	51	1273	Ductile
	-621 (Ecor)	7.92	24	55	1290	Ductile
	-650	8.04	23	53	1251	Ductile
	-850	8.26	25	55	1295	Ductile

^a Conc = test solution concentrations.^b E = controlled potential; Ecor = corrosion potential measured versus SCE.^c t_f = time to failure.^d El = elongation of test specimen based on 1.5-in gage length.^e RA = reduction of test specimen cross-section area.^f UTS = ultimate tensile strength of test specimen.

TABLE VII

Slow Strain Rate Tests on 4340 High Strength SteelExposed to NH_4NO_3 Solutions at pH of 3, Room Temperature.Strain Rate of $2.7 \times 10^{-6}/\text{s}$

Conc ^a ppm	E ^b mV vs SCE	t _f ^c hrs	El ^d %	RA ^e %	UTS ^f MPa	Fracture
Test in Vegetable Oil		8.20	24	55	1275	Ductile
10,000 ppm						
	-350	7.72	23	51	1251	Ductile
	-450	7.68	23	50	1251	Ductile
	-589 (Ecor)	7.72	23	52	1273	Ductile
	-650	7.11	21	50	1141	Ductile
	-850	1.36	4	1	1097	Brittle
1,000 ppm						
	-350	8.05	24	52	1273	Ductile
	-450	7.90	23	55	1273	Ductile
	-595 (Ecor)	8.29	24	55	1295	Ductile
	-650	8.31	24	53	1220	Ductile
	-850	1.77	5	1	1141	Brittle
100 ppm						
	-350	8.27	25	55	1251	Ductile
	-450	8.16	24	52	1295	Ductile
	-608 (Ecor)	8.43	24	54	1247	Ductile
	-650	8.34	24	54	1273	Ductile
	-850	3.28	10	2	1141	Brittle

^a Conc = test solution concentrations.^b E = controlled potential; Ecor = corrosion potential measured versus SCE.^c t_f = time to failure.^d El = elongation of test specimen based on 1.5-in gage length.^e RA = reduction of test specimen cross-section area.^f UTS = ultimate tensile strength of test specimen.

TABLE VIII

Slow Strain Rate Tests on 4340 High Strength SteelExposed to NH₄NO₃ Solutions at pH of 5, Room Temperature.Strain Rate of 2.7×10^{-6} /s

Conc ^a ppm	E ^b mV vs SCE	t _f ^c hrs	El ^d %	RA ^e %	UTS ^f MPa	Fracture
Test in Vegetable Oil						
		7.80	36	60	1207	Ductile
10,000 ppm						
	-350	7.20	29	50	1165	Ductile
	-450	7.52	30	55	1186	Ductile
	-627 (Ecor)	8.12	32	58	1158	Ductile
	-650	7.32	30	56	1178	Ductile
	-850	1.63	6	0	1074	Brittle
1,000 ppm						
	-350	7.74	31	51	1207	Ductile
	-450	7.89	32	54	1276	Ductile
	-629 (Ecor)	7.61	27	56	1186	Ductile
	-650	7.21	29	56	1165	Ductile
	-850	7.14	29	28	1179	Brittle & ductile
100 ppm						
	-350	7.94	31	58	1250	Ductile
	-450	7.75	30	55	1256	Ductile
	-639 (Ecor)	7.45	29	52	1206	Ductile
	-650	7.02	30	53	1207	Ductile
	-850	7.31	29	55	1229	Ductile

^a Conc = test solution concentrations.^b E = controlled potential; Ecor = corrosion potential measured versus SCE.^c t_f = time to failure.^d El = elongation of test specimen based on 1.5-in gage length.^e RA = reduction of test specimen cross-section area.^f UTS = ultimate tensile strength of test specimen.

TABLE IX

Slow Strain Rate Tests on 4340 High Strength SteelExposed to NH₄NO₃ Solutions at pH of 7, Room Temperature.Strain Rate of 2.7×10^{-6} /s

Conc ^a ppm	E ^b mV vs SCE	t _f ^c hrs	El ^d %	RA ^e %	UTS ^f MPa	Fracture
Test in Vegetable Oil		8.20	24	55	1275	Ductile
10,000 ppm						
	-350	7.75	23	52	1211	Ductile
	-450	8.18	23	54	1255	Ductile
	-631 (Ecor)	8.10	24	52	1247	Ductile
	-650	8.14	24	53	1251	Ductile
	-850	6.67	19	48	1229	Ductile
1,000 ppm						
	-350	7.90	23	55	1251	Ductile
	-450	7.86	23	54	1251	Ductile
	-632 (Ecor)	8.34	24	54	1229	Ductile
	-650	8.12	24	51	1273	Ductile
	-850	7.27	21	47	1229	Ductile
100 ppm						
	-350	7.83	23	55	1295	Ductile
	-450	7.60	24	52	1273	Ductile
	-637 (Ecor)	7.93	24	52	1251	Ductile
	-650	7.91	23	53	1290	Ductile
	-850	7.27	21	47	1229	Ductile

^a Conc = test solution concentrations.^b E = controlled potential; Ecor = corrosion potential measured versus SCE.^c t_f = time to failure.^d El = elongation of test specimen based on 1.5-in gage length.^e RA = reduction of test specimen cross-section area.^f UTS = ultimate tensile strength of test specimen.

TABLE X

Normalized^a Time to Failure, Reduction of Area
and Ultimate Tensile Strength of Specimens Subjected to
Slow Strain Rate Tests in NH₄Cl, KCl, and NH₄NO₃ Solutions
at pHs of 3 and 7

E ^b	100 ppm			1,000 ppm			10,000 ppm		
	t _f	RA	UTS	t _f	RA	UTS	t _f	RA	UTS
NH ₄ Cl, pH = 3									
-350	0.94	0.96	0.98	0.80	0.93	0.90	0.78	0.91	0.92
-450	0.95	0.98	0.98	0.86	0.93	0.93	0.78	0.93	0.97
Ecor	0.88	0.96	0.92	0.92	0.98	0.98	0.87	1.00	0.95
-650	0.92	1.00	0.93	0.72	0.93	0.93	0.95	1.00	0.90
-850	0.40	0.04	0.88	0.40	0.02	0.92	0.39	0.02	0.95
NH ₄ Cl, pH=7									
-350	0.80	0.93	0.93	0.90	0.98	0.97	0.76	0.93	0.93
-450	0.82	0.95	0.97	0.99	0.96	0.98	0.79	0.93	0.95
Ecor	0.96	1.00	1.00	0.96	1.00	1.00	0.91	1.00	1.00
-650	0.98	0.98	0.98	0.97	0.96	1.00	0.91	0.98	0.93
-850	0.86	1.00	0.92	0.80	0.44	0.90	0.74	0.29	0.86
KCl, pH=3									
-350	0.94	0.96	0.88	0.89	0.91	0.95	0.67	0.85	0.87
-450	0.96	1.00	0.95	0.83	0.95	0.93	0.88	0.95	0.94
Ecor	0.95	0.98	0.90	0.86	0.93	0.89	0.92	1.00	0.93
-650	0.90	0.93	0.92	0.91	0.96	0.92	0.91	0.98	0.95
-850	0.18	0.02	0.85	0.33	0.02	0.90	0.56	0.02	0.92
KCl, pH=7									
-350	0.88	0.95	1.00	0.87	0.93	0.93	0.88	0.91	0.92
-450	0.96	0.93	0.98	0.92	1.00	1.00	0.84	0.95	0.96
Ecor	0.93	1.00	1.00	0.90	1.00	0.98	0.98	1.00	1.07
-650	0.95	0.96	0.97	0.93	0.96	1.00	0.88	0.84	0.86
-850	0.97	1.00	1.00	0.90	0.98	0.98	0.53	0.07	0.75
NH ₄ NO ₃ , pH=3									
-350	0.97	1.00	0.97	0.95	0.95	0.98	0.91	0.93	0.97
-450	0.96	0.95	1.00	0.93	1.00	0.98	0.90	0.91	0.97
Ecor	0.99	0.98	0.96	0.98	1.00	1.00	0.91	0.95	0.98
-650	0.98	0.98	0.98	0.98	0.96	0.94	0.84	0.91	0.88
-850	0.39	0.04	0.88	0.21	0.02	0.88	0.16	0.02	0.85
NH ₄ NO ₃ , pH=7									
-350	0.92	1.00	1.00	0.93	1.00	0.97	0.91	0.95	0.94
-450	0.89	0.95	0.98	0.92	0.98	0.97	0.96	0.98	0.97
Ecor	0.93	0.95	0.97	0.98	0.98	0.95	0.95	0.95	0.96
-650	0.93	0.96	1.00	0.96	0.93	0.98	0.96	0.96	0.97
-850	0.86	0.85	0.95	0.86	0.85	0.95	0.78	0.80	0.95

^a Normalized values represent the ratio of the test results in corrosive environments versus in an inert environment.

^b Ecor = corrosion potential measured mV vs SCE.

Figure 1. Test Equipment and Electrical Connections in Controlled Potential Slow Strain Rate Tests

- (a) 10 000 ppm
- (b) 1 000 ppm
- (c) 100 ppm

Figure 2 - Normalized Time-To-Failure of Specimens Tested in Solutions Containing 100, 1 000, and 10 000 ppm of Ammonium Chloride at Ambient Temperature and Strain Rate of $2.7 \times 10^{-6}/s$

- (a) 10 000 ppm
- (b) 1 000 ppm
- (c) 100 ppm

Figure 3 - Normalized Reduction of Area of Specimens Tested in Solutions Containing 100, 1 000, and 10 000 ppm of Ammonium Chloride at Ambient Temperature and Strain Rate of $2.7 \times 10^{-6}/s$

- (a) 10 000 ppm
- (b) 1 000 ppm
- (c) 100 ppm

Figure 4 - Normalized Time-To-Failure of Specimens Tested in Solutions Containing 100, 1 000, and 10 000 ppm of Potassium Chloride at Ambient Temperature and Strain Rate of $2.7 \times 10^{-6}/s$

- (a) 10 000 ppm
- (b) 1 000 ppm
- (c) 100 ppm

Figure 5 - Normalized Reduction of Area of Specimens Tested in Solutions Containing 100, 1 000, and 10 000 ppm of Potassium Chloride at Ambient Temperature and Strain Rate of 2.7×10^{-6} /s

- (a) 10 000 ppm
- (b) 1 000 ppm
- (c) 100 ppm

Figure 6 - Normalized Time-To-Failure of Specimens Tested in Solutions Containing 100, 1 000, and 10 000 ppm of Ammonium Nitrate. at Ambient Temperature and Strain Rate of 2.7×10^{-6} /s

- (a) 10 000 ppm
- (b) 1 000 ppm
- (c) 100 ppm

Figure 7 - Normalized Reduction of Area of Specimens Tested in Solutions Containing 100, 1 000, and 10 000 ppm of Ammonium Nitrate at Ambient Temperature and Strain Rate of 2.7×10^{-6} s