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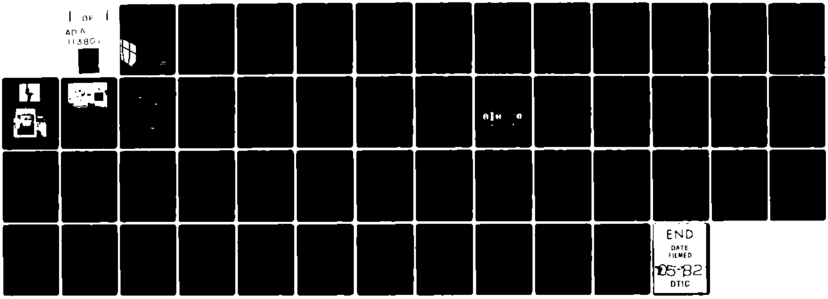

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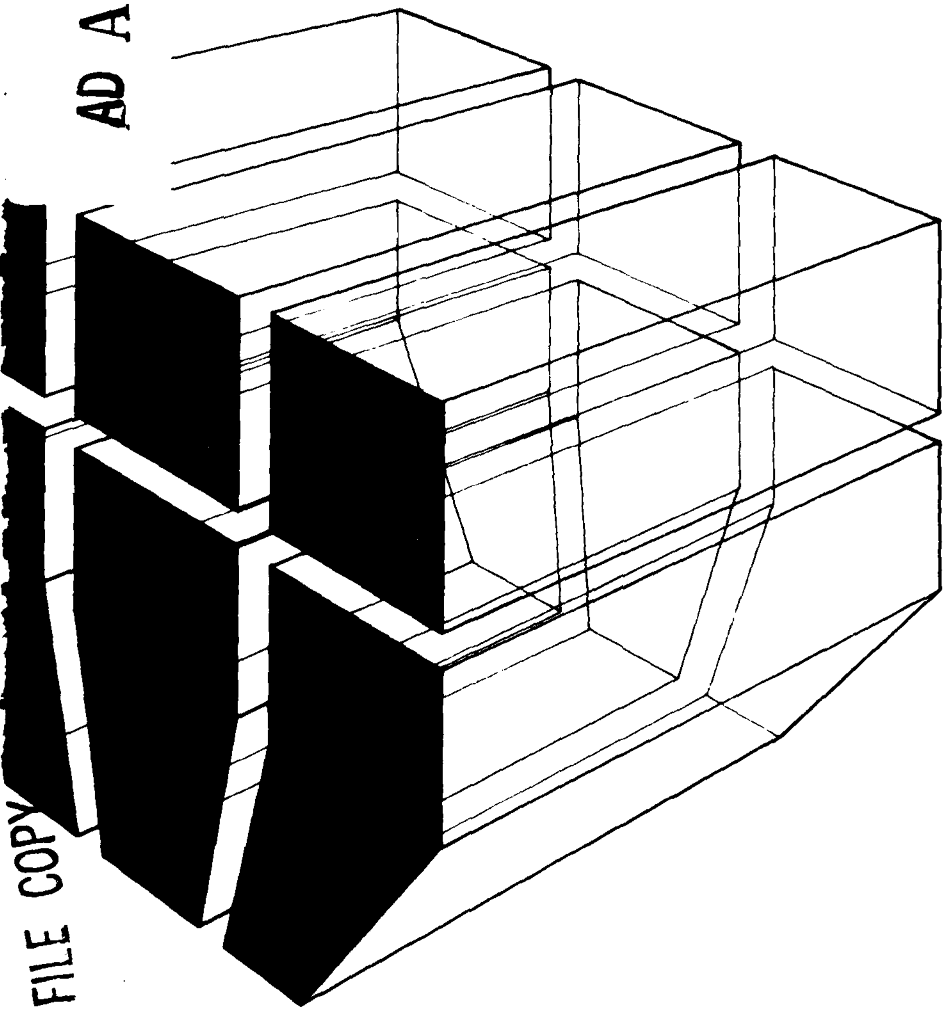
March 1982
Fasteners for Machinery and Appurtenances
in Civil Works Hydraulic Structures

WROUGHT STAINLESS STEEL FASTENERS FOR CIVIL WORKS APPLICATIONS



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This report presents the results of an investigation conducted by the U.S. Army Construction Engineering Research Laboratory (CERL) into the mechanical properties, corrosion resistance, and cost of eight wrought stainless steels with the potential for use in Civil Works applications. It was concluded that no single stainless steel can be selected for optimum performance under all conditions. Thus, a Fastener Selection Guide was developed to help the design engineer select wrought stainless steels for fasteners and other components in Civil Works structures.

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FOREWORD

This study was conducted for the Directorate of Civil Works, Office of the Chief of Engineers (OCE), under CWIS 31660, "Fasteners for Machinery and Appurtenances in Civil Works Hydraulic Structures." The OCE Technical Monitor was Mr. J. Robertson, DAEN-CWE-E.

This research was performed by the Engineering and Materials (EM) Division of the U.S. Army Construction Engineering Research Laboratory (CERL). Cavitation and galling tests were conducted at the U.S. Bureau of Reclamation, Denver, CO by Mr. H. Uyeda. Dr. R. Quattrone is Chief of CERL-EM.

COL Louis J. Circeo is Commander and Director of CERL and Dr. L. R. Shaffer is Technical Director.

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WROUGHT STAINLESS STEEL FASTENERS FOR CIVIL WORKS APPLICATIONS

1 INTRODUCTION

Background

Civil Works pumping stations and turbine generators can cost millions of dollars to build and maintain. An almost insignificant part of this expense is for high-strength bolts used to anchor pumps, turbines, and join pump flanges. However, some of the bolts now used in Civil Works Systems have failed in less than 5 years. Such failures can cause dangerous downtimes and significantly increase operation and maintenance costs.[1] In many cases, the cost of the material for the failed part is negligible compared to the repair cost and the consequent losses in navigation and/or hydroelectric power production.

The U.S. Army Corps of Engineers has been using Type 304 stainless steel (SS) for Civil Works applications where good corrosion resistance is needed. Although Type 304 SS resists corrosion well enough in most environments, its yield strength is limited to 40 ksi (276 MN/m^2) in sections larger than 5 cm (50 mm) in diameter. As an alternate, the Corps has used Type 410 SS where higher yield strengths are needed, but 410 SS does not have adequate corrosion and stress corrosion resistance. Type 410 SS is also very sensitive to heat treatment; improperly heat treated 410 SS has failed in some Civil Works structures.

Although the Corps' use of stainless steels in Civil Works applications has been limited to Types 304 and 410, many new types are being used or modified for use each year. For example, precipitation hardened stainless steels, which are about twice as strong as 304 SS, are being applied with much success by high-technology private industry. Thus, the Office of the Chief of Engineers, Directorate of Civil Works, asked the U.S. Army Construction Engineering Research Laboratory (CERL) to investigate stainless steel alloys other than types 304 and 410 to determine which, if any, have potential for improving fastener performance in Civil Works Systems.

Objective

The objective of this study was to develop a fastener selection guide to help the Civil Works design engineer select wrought stainless steels on the basis of corrosion resistance, mechanical properties, and cost.

Approach

Newly developed stainless steels with potential for Civil Works applications were identified. Available data on chemical composition, heat treatment, and mechanical properties were collected. Vendors' data were validated and additional measurements of interest to Corps Civil Works structure applications were conducted. The uniform corrosion resistance, pitting resistance, galvanic compatibility with carbon steels, galling resistance, cavitation corrosion resistance, and dynamic fracture toughness of the steels were measured in the laboratory. Information concerning mechanical properties, stress corrosion cracking (SCC) behavior, and cost were compiled.

Mode of Technology Transfer

This study will impact the revision of Civil Works Guide Specifications CW 05501, *Metal Fabrication, Machine Work and Miscellaneous Provisions* and CW 05502, *Miscellaneous Metal Materials, Standard Articles, and Shop Fabricated Items*.

2 SELECTING STAINLESS STEELS FOR CIVIL WORKS STRUCTURES

Criteria for Materials Selection

Fasteners used for machinery and appurtenances in Civil Works hydraulic structures are exposed to corrosive environments, relatively high mechanical stresses (both static and dynamic), abrasion wear, and contact with dissimilar metals.

Materials selected for these fasteners should be inexpensive, readily available, and have the following properties:

1. Low uniform corrosion rate.

2. Resistance to pitting and crevice corrosion.

3. Electrochemical compatibility with other metals in the structure (to minimize galvanic corrosion).

4. Resistance to concentration cell corrosion.

5. Resistance to SCC and corrosion fatigue.

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[1] J. Aleszka, *Failure Analysis of Tainter Gate Cable-Adjusting Bolts*, Technical Report (TR) M-120/ADA008996 (U.S. Army Construction Engineering Research Laboratory [CERL], April 1975); and A. Kumar, R. Lampo, and F. Kearney, *Cathodic Protection of Civil Works Structures*, TR M-276/ADA080057 (CERL, December 1979).

6. Resistance to erosion corrosion and cavitation.

7. High strength and toughness.

8. Mechanical compatibility with other metals in the structure (to avoid fastener or structure failures caused by galling or seizure).

Stainless Steels for Civil Works Applications

The optimization of certain metal properties can reduce or eliminate other desirable features. For example, some extremely corrosion resistant materials are prohibitively expensive; others, like the 300 series stainless steels, give up strength for improved corrosion resistance. Therefore, the selection of fastener materials requires a compromise to ensure that these materials will exhibit the optimized properties under specific conditions.

The Corps has traditionally used 400 series stainless steels for Civil Works structure fasteners where high strength is needed. However, these steels are extremely sensitive to heat treatment and are not very corrosion resistant. There are many other available grades of stainless steels such as the precipitation hardenable grades; some have properties superior to those of the 400 series steels that make them candidates for use in Civil Works structures.

Many stainless steels are available in both wrought and cast form; only wrought grades which could be cold or hot worked and had properties with potential for Civil Works applications were considered for this study. Eight grades of stainless steels were selected on the basis of desirable properties for Civil Works applications: 304 SS, 410 SS, Carpenter Custom 450 SS, Carpenter Custom 455 SS, 17-4 PH SS, PH 13-8 Mo SS, Nitronic 50 (N50) SS, and Nitronic 60 (N60) SS.

The properties, metallurgy, and modes of corrosion of the steels selected for this investigation are detailed in Appendix A.

3 PROCEDURE

One-inch (24.5-mm) diameter rods of the test stainless steels were machined to appropriately sized samples. The chemical composition and mechanical properties of these sample alloys are shown in Tables 1 and 2, respectively.

Potentiodynamic Tests

Potentiodynamic tests were conducted using a Princeton Applied Research (PAR) Model 350 corrosion measurement system. These tests were done in 1N H_2SO_4 and 1N H_2SO_4 with 0.5M NaCl with bubbled nitrogen gas. Potentiodynamic tests in Columbia River water bubbled with air were conducted on PAR corrosion systems consisting of a Model 175 universal programmer, a Model 173 potentiostat/galvanostat with a Model 376 logarithmic current converter module, and a standard Greene cell. Specimens were degreased, polished to a 600-grit surface finish, and mounted in a flat specimen holder exposing 1 cm^2 ($100mm^2$) of metal. Corrosion cell potentials were allowed to stabilize before starting the scans; the corrosion potential vs a saturated calomel electrode (SCE) of each sample was noted. Scans were performed at a rate of 0.1 mV/s and terminated at potentials where samples visibly were corroding rapidly with associated high currents. An SCE was used for all electromotive force (emf) measurements.

Galvanic Tests

A PAR Model 350 corrosion measurement system was used to determine the electromotive series and corrosion rates of the stainless steels. Tests were performed in 0.5M NaCl in distilled water solutions.

The emf series measurements were obtained by measuring the potential of test stainless steel samples (and A36 steel) vs an SCE. This measurement was taken 10 s after immersion in 0.5M NaCl solution. Samples were degreased and polished to a 600-grit finish before the emf measurements.

Corrosion currents were measured by coupling stainless steel specimens to A36 steel and measuring the current after 4 hours of immersion in 0.5M NaCl purged with air. Both the test sample and the A36 steel consisted of 0.75 in. (18 mm) diameter rods 0.5 in. (12 mm) thick. The two steels were mounted 0.25 in. (6 mm) apart in a holder exposing only the circumference of each sample.

Cavitation Tests

Cavitation tests were conducted essentially in accordance with ASTM G-32, *Standard Method of Vibratory Cavitation Erosion Test*. The vibratory test apparatus was a Lab-line No. 9100 Ultratip Labsonic System (Figure 1). Tests were conducted at a generator output of 125 W, which corresponds to a resonant frequency of 21 kHz and a peak-to-peak displacement amplitude of 2.2 mils (as determined by oscillographic and filar

Table 1
Chemical Composition of Test Alloys*

Alloy Designation	C	Mn	P	S	Si	Percent by weight Cr	Ni	Mo	Cu	Co	Other Elements
304 austenitic SS	0.06	1.39	0.019	0.57	1.00	18.33	8.67	0.42	0.20	0.170	N - 0.079, Fe - balance
410 martensitic SS	0.125	0.49	0.024	0.011	0.23	11.73	0.13	0.15	0.08	0.017	Al - 0.005, N - 0.053, Sn - 0.01, Fe - balance
Carpenter Custom 450 SS**	0.05	1.0	0.03 (max)	0.03 (max)	1.0	14.00–16.00	5.0–7.0	0.5–1.0	1.25–1.75		Fe - balance
Carpenter 455 SS**	0.05	1.0			1.0	14.00–16.00	5.0–7.0	1.00	1.75		Fe - balance
Armco 17-4 PH SS	0.038	0.68	0.040	0.004	0.32	15.63	4.85	0.30	3.51	0.080	Ta - 0.01, Cb - 0.26, Fe - balance
Armco PH 13-8 Mo SS	0.03	0.03	0.003	0.004	0.02	12.58	8.15	2.14			Al - 1.13, N - 0060
Armco N50 SS	0.034	5.25	0.014	0.004	0.44	21.09	12.70	2.30	0.03		Cb - 0.03, N - 0.16, V - 0.18
Armco N60 SS	0.070	8.18	0.029	0.0073	0.98	17.06	8.50	0.19	0.30		N - 0.13, Fe - balance
4130 low alloy steel	0.30	0.56	0.006	0.013	0.26	0.95	0.16	0.22	0.11		Fe - balance

*From mill test reports, unless otherwise indicated.

**Mill test reports unavailable; nominal composition from handbooks shown.

Table 2
Mechanical Properties of Test Alloys*

	Mechanical Properties			
Alloy Designation	*Yield* Strength (ksi)	*Ultimate* Strength (ksi)	Elongation (% in 2 in.)	Hardness (*Brinell No.*)
304 austenitic SS	66	99	47.0	197
410 martensitic SS	77	104	25.0	223
Carpenter Custom 450 SS**	117	144	14.0	270
Carpenter Custom 450 SS (heat treated)**, ++	184	196	16.0	320
Carpenter 455 SS**	117	14	14.0	311
Carpenter 455 SS (heat treated)**, ++	218	226	11.0	418
Armco 17-4 PH SS**	110	150	12	321
Armco 17-4 PH SS (heat treated)**, +	182.5	192.7	15.9	388
Armco PH 13-8 Mo SS**	100	160	15	331
Armco PH 13-8 Mo SS (heat treated)**	216.0	228.0	14.0	444
Armco N50 SS	80	128	40.0	248
Armco N60 SS	52	104	60.0	201
4130 low alloy steel	124.3	139.5	20	28.6

*From mill test reports unless otherwise indicated. Metric conversions: 1 ksi = N-m; 1 in. = 24.5 mm; (°F-32)/1.8 = °C.

**Mill test reports not available, nominal properties from handbooks shown.

+Heated to and maintained at 1,150°F for 4 hours and cooled slowly.

++Heated to and maintained at 1,050°F for 4 hours and cooled slowly.

Note: The American Society for Testing and Materials (ASTM) Standard for the mechanical testing of steels is *Standard Methods and Definitions for Mechanical Testing of Steel Products*, ANSI/ASTM A370-77 (ASTM, 1977).

microscopic measurements, respectively). The Labline equipment uses a hexagonal-faced test specimen with a short diameter of 0.4946 in. (12.56 mm), resulting in a test surface area of 0.2119 sq in. (136.7 mm^2). The test surface was finally ground to a 10-rms* finish.

The specimens were exposed until a steady-state erosion rate was obtained; this rate was determined gravimetrically. The erosion rate was calculated from the weight loss rates by correcting for specimen surface area and test alloy density. Duplicate tests were conducted for each material.

Galling Tests

The galling tests were conducted similar to ASTM D2670-67, *Standard Method for Measuring Wear Properties of Fluid Lubricants (Falex Method)* (ASTM, 1977), using a Falex friction and wear testing machine, pin and vee block model (Figures 2 and 3). Journals and vee blocks of the test alloys were prepared, cleaned, and placed in the equipment; deionized water was used as the lubricant. The temperature of the water at the start of the test was 73°F (22°C). Following a run-in period of 3 minutes with a direct load of 200 lb (91 kg), the load was increased in 50-lb (22-kg) increments, using the automatic ratchet loading mechanism (the load was maintained at each load for 1-minute periods). This process was repeated until the

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*root mean square

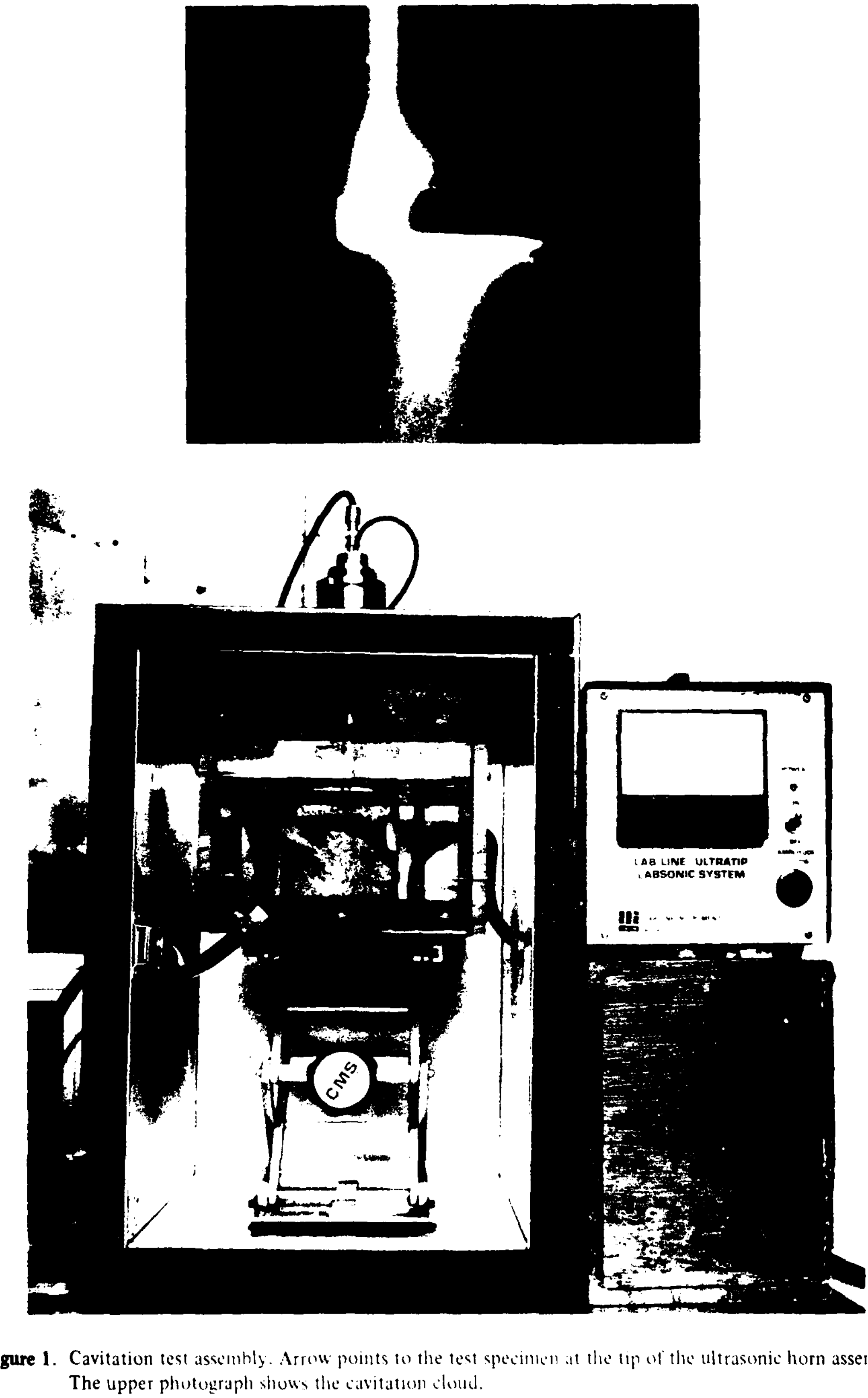

Figure 1. Cavitation test assembly. Arrow points to the test specimen at the tip of the ultrasonic horn assembly. The upper photograph shows the cavitation cloud.

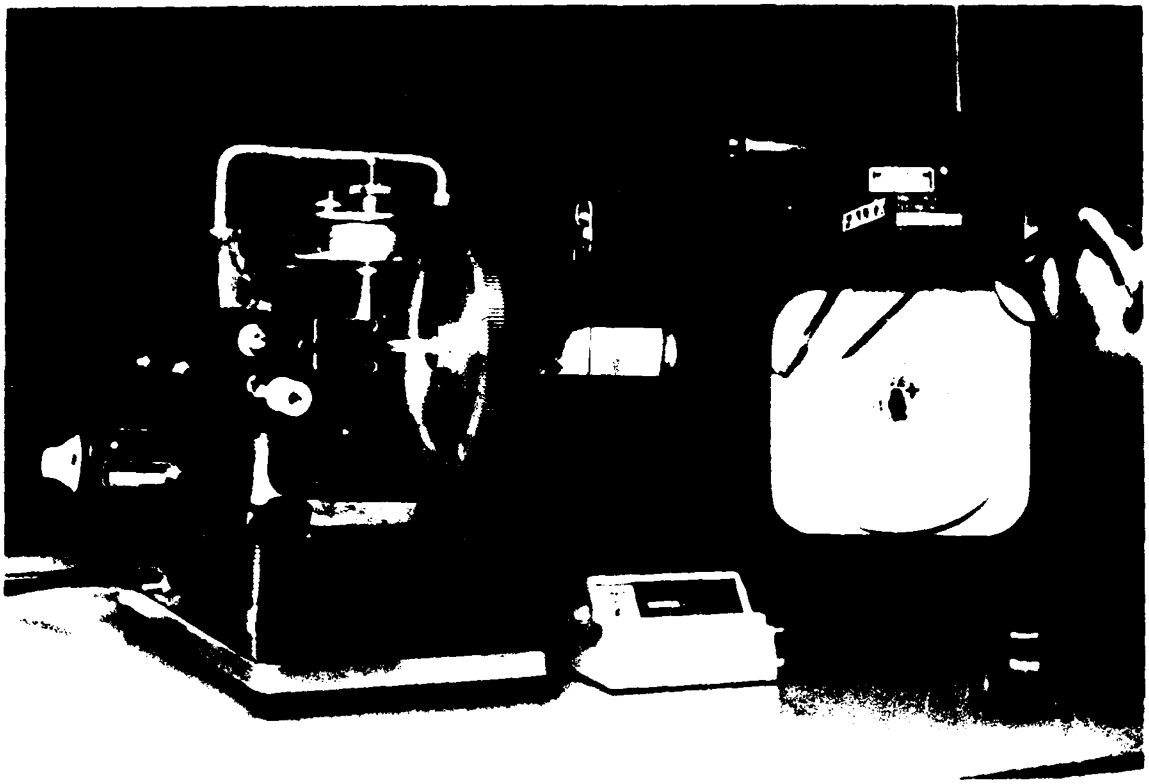

Figure 2. Falex friction and wear testing apparatus. Arrow points out the test specimen (journal and vee blocks).

direct load exceeded 1000 lb (453 kg), the torque exceeded 55 in.-lb (6.21 N-m), or the locking pin seized or sheared. No effort was made to control the temperature of the water, which sometimes reached the boiling point. At the conclusion of each test, the journals and vee blocks were examined to determine the mode of failure. The coefficients of friction were determined from the maximum torque and direct load data, and from the test specimen geometry using the following formula:

$$\mu = \frac{2.97\ T}{DL} \qquad \text{[Eq 1]}$$

where: μ = coefficient of friction
T = maximum torque
DL = direct load

Dynamic Fracture Toughness Tests

Dynamic fracture toughness tests of the steels were performed at 72, 32, and −60° F (22, 0, and −51° C) according to Koppenaal's procedure.[2]

4 RESULTS AND DISCUSSION

Potentiodynamic Scans

Potentiodynamic scans of the 12 steels in 1N H_2SO_4, 1N H_2SO_4 with 0.5M NaCl, and Columbia River water are shown in Appendix B (Figures B1 through B12). Corrosion potential, primary passivation current and voltage, passive voltage ranges, and average passive currents for each steel in each solution were determined from potentiodynamic scans. These results are summarized for the stainless steels in Columbia River water, 1N H_2SO_4, and 1N H_2SO_4 with 0.5M NaCl in Tables 3, 4, and 5, respectively.

Table 3 shows that all the steels were passive in Columbia River waste. Corrosion current increased with increasing anodic potential up to a potential of E_I (with an associated current, I_I). The corrosion current then remained relatively constant with increasing potential up to a potential of E_t (with an associated current I_t), where transpassive behavior (i.e., breakdown) with accelerated corrosion began. This table also shows the corrosion potential (E_{corr}), E_1, I_1, E_t, and I_t for each steel. Corrosion currents of all the steels in

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[2] T. J. Koppenaal, *Dynamic Fracture Toughness Measurements of High-Strength Steels Using Precracked Charpy Specimens*, ASTM Special Technical Publication 563 (American Society for Testing and Materials [ASTM], 1974), pp. 92-117.

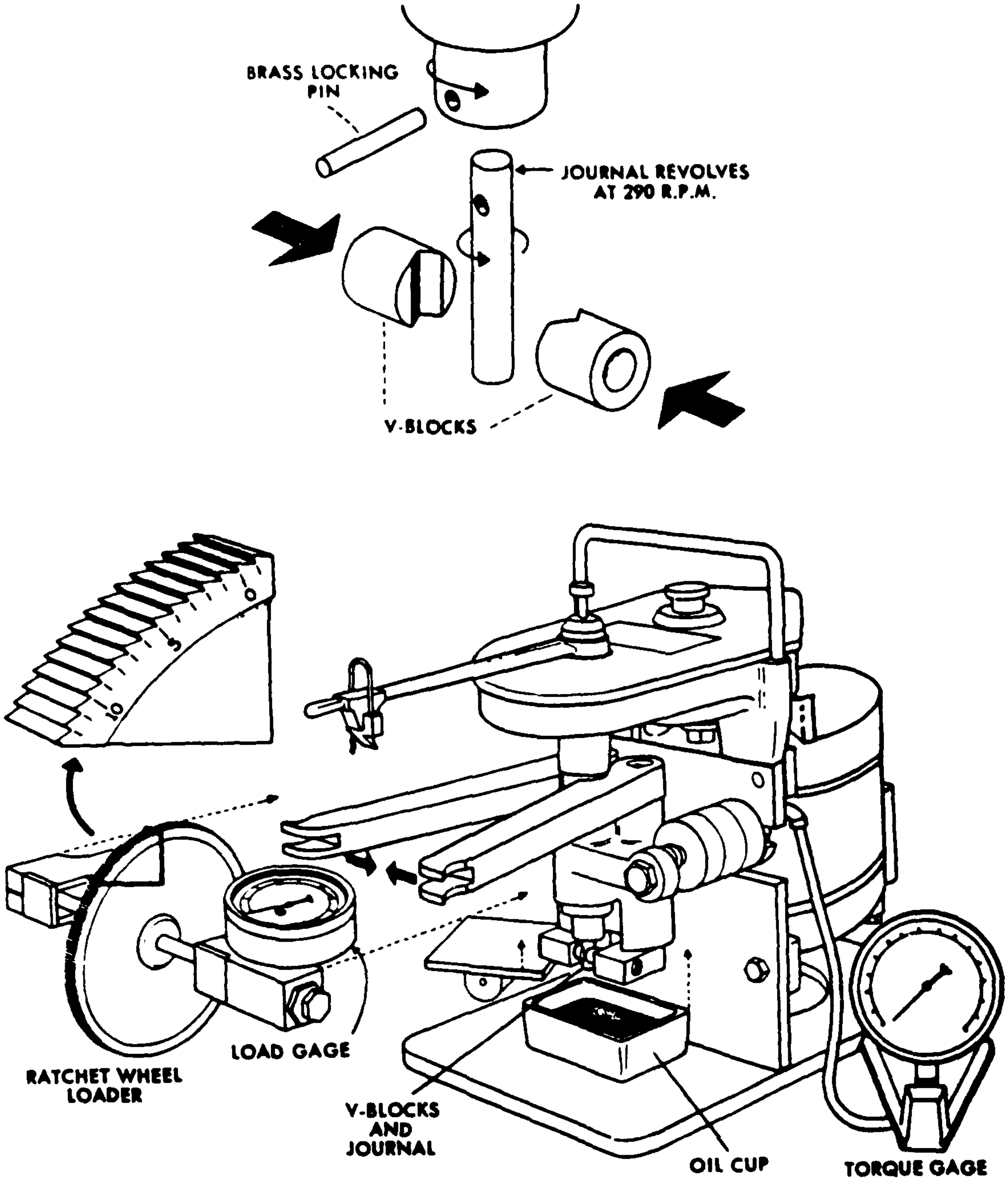

Figure 3. Sketch of Falex friction and wear test apparatus. Enlarged schematic of journal and vee blocks appears above.

the anodic passive range were on the order of 10^{-7} A/cm^2 (10^{-9} A/mm^2). However, 410 SS exhibited a much narrower passive range than the other steels. This behavior suggests that 410 SS is more susceptible to pitting than the other steels.

Tables 4 and 5 summarize the results of potentiodynamic scans of the stainless steels in 1N H_2SO_4 and 1N H_2SO_4 with 0.5M NaCl, respectively. Tables 4 and 5 list E_{corr}, primary passivation potential and current (E_{pp} and I_{pp}), range of the constant current passive region (E_p - E_t), and the average corrosion current in the passive region (I_{ave}). Again, at applied potentials above E_t, the steels exhibit transpassive behavior with associated accelerated corrosion rates.

Table 4 shows that in 1N H_2SO_4 purged with nitrogen to limit oxygen accessibility, only N50 was naturally passive. The steels all exhibited passive currents on the order of 10^{-6} A and breakdown (E_t) at about 0.9 V (SCE). Table 5 shows that none of the steels were naturally passive in 1N H_2SO_4 with 0.5M NaCl, and that 410 SS did not exhibit any passivity in this solution.

The addition of NaCl to the sulfuric acid resulted in breakdown voltages and higher passive currents that ranged from 10^{-6} to 10^{-4} A/cm^2 (10^{-8} to 10^{-6} A/mm^2). The effect of NaCl in H_2SO_4 on the corrosion of the steels was quantified by determining the reduction of the passive potential range when the sulfuric acid solution contained 0.5M NaCl. The following equation was used to determine the percent reduction in passive region (% RP) for each steel shown in Table 5:

$$\% RP = 100 \times 1 - \frac{E_t - E_p\,(1N\ H_2SO_4 + 0.5M\ NaCl)}{E_t - E_p\,(1N\ H_2SO_4)} \qquad [Eq\ 2]$$

The 304 SS, N60, and N50 test samples exhibited the least reduction in the passive region (39 percent, 21 percent, and no effect, respectively), but the 304 SS and N60 samples exhibited the highest passive currents: 8.36×10^{-4} and 4.70×10^{-4} A/cm^2 (8.36×10^{-6} and 4.70×10^{-6} A/mm^2). The N50 sample exhibited a very low passive current: 2.02×10^{-6} A/cm^2 (2.02×10^{-8} A/mm^2). The passive regions of the other steels were reduced more than 60 percent, but passive currents remained below 5×10^{-5} A/cm^2 (5×10^{-7} A/mm^2).

The potentiodynamic scans in the three solutions showed that, with the exception of 410 SS, all of the steels exhibited similar anodic behavior in river water and sulfuric acid. The 410 SS sample was found to exhibit the poorest anodic behavior and the greatest sensitivity to attack by chloride-containing environments. The N50 sample exhibited the best resistance to accelerated corrosion due to the presence of chloride ions; the N50 and N60 samples had good resistance to breakdown, but exhibited high passive currents. The other steels exhibited similar resistance to attack by chloride ions, had relatively low passive currents, and chloride ions had a large effect on breakdown voltage.

Galvanic Tests

Table 6 shows the emf measurements for the test samples vs an SCE. The metals were ranked according to potential (V_0); the N50 sample was the most noble and A36 was the least noble. The second column in Table 6 shows the potential difference between each steel and A36 steel. All of the stainless steels are cathodic with respect to A36. The potential difference between these two metals provides the driving force for corrosion; the larger the potential difference, the greater the driving force. All the steels, except N50 and N60, were more compatible with A36 than 304 SS (based only on potential difference).

It should be noted that corrosion rates cannot be predicted based on potential difference alone. This measurement only defines anodic and cathodic materials coupled together in a particular environment. In different environments, two metals coupled together may exhibit a different anode and cathode than that predicted by the emf measurements.

Table 7 shows the results of galvanic current measurements of the steels tested coupled with A36 steel. The 410 SS/A36 sample exhibited the highest corrosion current; the N60/A36 sample exhibited the lowest corrosion current. The galvanic corrosion currents of 410 SS/A36, Custon 455 (H1050)/A36, 17-4 PH (ST)/A36, and N50/A36 couples were all higher than that of the 304 SS/A36 couples; couples with the other steels yielded lower galvanic currents. In all cases, the A36 was the anode in the corrosion circuit.

Cavitation Tests

Table 8 lists the results of the cavitation tests. The test materials, ranked in order of their relative cavitation resistance in this test, are listed in Table 9. Figure 4 shows a typical specimen after testing.

Table 3
Summary of Potentiodynamic Scans of Stainless Steels in Columbia River Water*

	304 SS	410 SS	Custom 450 (ST)	Custom 450 (H1150)	Custom 455 (ST)	Custom 455 (H1050)	17-4 PH (ST)	17-4 PH (H1150)	PH 13-8 Mo (ST)	PH 13-8 Mo (H1150)	N50	N60
E_{corr}, V(SCE)	−0.181	−0.153	−0.917	0.072	−0.822	−0.227	−0.116	−0.120	0.80	0.110	−0.093	−0.077
E_1, V(SCE)	0.02	0.03	0.12	0.04	0.12	−0.08	0.06	0.09	0.03	0.07	0.08	0.12
I_1, A/cm^2	5.4×10^{-7}	5.8×10^{-7}	3.8×10^{-7}	2.8×10^{-7}	5.0×10^{-7}	4.4×10^{-7}	5.3×10^{-7}	5.2×10^{-7}	4.8×10^{-7}	4.4×10^{-7}	4.9×10^{-7}	8.2×10^{-7}
E_t, V(SCE)	0.68	0.34	1.59	1.27	0.98	0.84	0.98	1.02	0.99	1.04	0.99	1.04
I_t, A/cm^2	8.9×10^{-7}	5.8×10^{-7}	5.9×10^{-7}	1.3×10^{-6}	6.8×10^{-7}	5.5×10^{-7}	6.9×10^{-7}	8.8×10^{-7}	7.4×10^{-7}	6.4×10^{-7}	6.7×10^{-7}	9.2×10^{-7}

*Metric conversion: 1 A/cm^2 = 0.01 A/mm^2.

Table 4
Summary of Potentiodynamic Scans of Stainless Steels in 1N H_2SO_4*

	304 SS	410 SS	Custom 450 (ST)	Custom 450 (H1150)	Custom 455 (ST)	Custom 455 (H1050)	17-4 PH (ST)	17-4 PH (H1150)	PH 13-8 Mo (ST)	PH 13-8 Mo (H1150)	N50	N60
E_{corr}, V(SCE)	−0.464	0.500	−0.296	−0.320	−0.328	−0.472	−0.338	−0.449	−0.362	0.366	0.086	0.448
E_{pp}, V(SCE)	0.347	0.376	−0.256	−0.277	−0.260	−0.427	−0.269	−0.312	0.276	0.261	passive	0.346
I_{pp}, A/cm^2	4.28×10^{-4}	1.49×10^{-2}	3.68×10^{-5}	2.63×10^{-5}	1.08×10^{-4}	7.64×10^{-4}	1.60×10^{-4}	8.75×10^{-5}	3.07×10^{-5}	2.93×10^{-5}	passive	3.63×10^{-4}
E_p, V(SCE)	0.05	0.20	0.11	0.01	0.10	0.22	0.07	0.02	0.10	0.02	0.09	0.08
E_t, V(SCE)	0.89	0.81	0.92	0.87	0.93	0.91	0.89	0.88	0.92	0.90	0.90	0.92
I_{ave}	3.27×10^{-6}	5.27×10^{-6}	1.92×10^{-6}	2.00×10^{-6}	1.87×10^{-6}	3.88×10^{-6}	2.02×10^{-6}	2.53×10^{-6}	1.67×10^{-6}	2.05×10^{-6}	1.52×10^{-6}	1.58×10^{-6}

*Metric conversion: 1 A/cm^2 = 0.01 A/mm^2.

Table 5
Summary of Potentiodynamic Scans in 1N H_2SO_4 and 1M NaCl*

	304 SS	410 SS	Custom 450 (ST)	Custom 450 (H1150)	Custom 455 (ST)	Custom 455 (H1050)	17-4 PH (ST)	17-4 PH (H1150)	PH 13-8 Mo (ST)	PH 13-8 Mo (H1150)	N50	N60
E_{corr}, V(SCE)	-0.464	-0.504	0.374	0.424	0.366	-0.418	0.406	0.448	0.378	-0.394	0.342	0.440
E_{pp}, V(SCE)	-0.267	none	0.292	0.289	-0.259	-0.304	-0.300	0.316	0.290	0.323	-0.283	0.262
I_{pp}, A/cm^2	1.94×10^{-3}	none	1.13×10^{-3}	7.31×10^{-4}	3.83×10^{-3}	4.39×10^{-3}	9.38×10^{-4}	8.63×10^{-4}	1.24×10^{-3}	1.83×10^{-3}	8.36×10^{-5}	1.56×10^{-3}
E_p, V(SCE)	-0.17		-0.15	-0.05	0.00	0.02	-0.09	0.12	0.11	0.03	0.10	-0.18
E_t, V(SCE)	0.34		0.09	0.14	0.003	0.12	0.06	0.08	0.21	0.13	0.88	0.48
I_{ave}, A/cm^2	8.36×10^{-4}		3.78×10^{5}	8.25×10^{-6}	1.23×10^{-4}	1.47×10^{-4}	1.31×10^{-5}	1.17×10^{5}	4.59×10^{-5}	4.14×10^{-5}	2.02×10^{6}	4.70×10^{-4}
% Reduction in passive region	39.29	100%	76.70	78.41	96.38	85.51	81.70	76.74	60.98	89.13	no effect	21.43

*Metric conversion: 1 A/cm^2 = 0.01 A/mm^2.

Table 6
Electromotive Series Results*

Material	V_0, V(SCE)	Steel/A36, Couple, V
N50	−0.293	0.281
N60	−0.327	0.247
304 SS	−0.328	0.246
Custom 450 (ST)	0.330	0.244
PH 13-8 Mo (ST)	−0.350	0.224
Custom 450 (H1150)	−0.362	0.212
Custom 455 (H1050)	−0.362	0.212
PH 13-8 Mo (H1150)	−0.372	0.202
17-4 PH (H1150)	−0.384	0.190
Custom 455 (ST)	−0.384	0.190
17-4 PH (ST)	−0.396	0.178
410 SS	−0.488	0.086
A36	−0.574	0

**Potentials measured in 0.5M NaCl.*

Table 7
Galvanic Corrosion Results*

A36 Coupled With	I_g, A/cm²**
304 SS	2.10×10^{-5}
410 SS	2.5×10^{-5}
Custom 450 (ST)	2.0×10^{-5}
Custom 450 (H1150)	1.6×10^{-5}
Custom 455 (ST)	2.0×10^{-5}
Custom 455 (H1050)	2.3×10^{-5}
17-4 PH (ST)	2.2×10^{-5}
17-4 PH (H1150)	1.9×10^{-5}
PH 13-8 Mo (ST)	1.9×10^{-5}
PH 13-8 Mo (H1150)	1.9×10^{-5}
N50	2.2×10^{-5}
N60	1.4×10^{-5}

*Tests conducted in 0.5M NaCl.

**$A/cm^2 = 0.01\ A/mm^2$

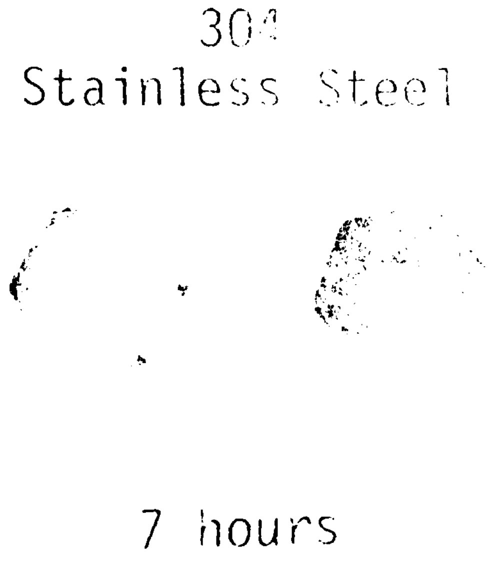

Figure 4. Surfaces of duplicate specimens of 304 austenitic SS after testing. Surfaces were machined to a 10-rms finish before testing.

The test method used in this study determined the rate of erosion based on the generation of cavitation bubbles that collapsed on the face of a test specimen vibrating at high frequency in water. This method can be used to determine the relative resistance of a variety of alloys to the effects of cavitation under standard specified conditions. Reportedly, the American Society for Testing and Materials (ASTM) has successfully completed a round robin test, resulting in the ASTM standard method.[3] The cavitation intensity using this method is such that steady-state erosion rates can be determined in a matter of hours (normally less than 8), even for the more highly resistant materials. Having such a rapid test available means that candidate materials can be screened quickly without resorting to other known mechanical properties such as hardness and such concepts as strain energy,[4] which has not been demonstrated to be a reliable indicator of a material's response in cavitation environments.

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[3] *Standard Method of Vibratory Cavitation Erosion Test,* ANSI/ASTM G32 (ASTM, 1977).

[4] T. E. Backstrom, *A Suggested Metallurgical Parameter in Alloy Selection for Cavitation Resistance,* USBR Laboratory Report No. ChE-72, (U.S. Bureau of Reclamation, December 1967).

Table 8
Results of Cavitation Tests*

Alloy Designation	Density (g/cm^3)	Weight Loss (mg)	Elapsed Time (hr)	Erosion Rate (in./yr)	Average Erosion Rate (in./yr)
304 austenitic SS	7.92	29.4	5.0	1.5	1.7
	7.92	28.1	5.0	1.8	
410 martensitic SS	7.75	56.6	5.0	3.7	3.8
	7.75	72.3	6.0	3.9	
Carpenter Custom 450 (ST)	7.81	22.2	4.0	1.8	1.9
	7.81	30.6	5.0	2.0	
Carpenter Custom 450 (heat treated)	7.67	14.3	6.0	1.2	1.3
	7.67	15.0	6.0	1.3	
Carpenter 455 (heat treated)	7.83	16.6	7.0	0.8	0.9
	7.83	22.1	8.0	0.9	
Armco 17-4 PH (ST)	7.78	26.1	5.0	1.7	1.6
	7.78	21.9	5.0	1.4	
Armco 17-4 PH (heat treated)	7.82	15.0	4.0	1.2	1.2
Armco PH 13-8 Mo	7.47	21.2	5.0	1.4	1.5
	7.47	22.0	5.0	1.5	
Armco PH 13-8 Mo (heat treated)	7.80	20.6	4.0	1.7	1.5
	7.80	16.3	4.0	1.3	
Armco N60	7.64	12.7	12.0	0.4	0.4
	7.64	10.8	12.0	0.3	
4130 low alloy steel	7.86	22.6	3.0	2.4	2.5
	7.86	30.6	4.0	2.5	

*Metric conversions: 1 g/cm^2 = 100 g/mm^2; 1 in./yr = 24.5 mm/yr.

The Armco N60 material, which performed best in this test, is a relatively new stainless steel. It is a nominal 18-8 chromium nickel austenitic stainless steel that is nitrogen modified. It reportedly possesses about the same corrosion resistance as 304 SS and is easy to weld, an important consideration when selecting materials for repairing pump and turbine components.[5]

The 17-4 PH precipitation hardenable SS, the 304 austenitic SS, and the Carpenter Custom 450 SS all had about the same response to the effects of the cavitation test used in this study. These steels are iron alloys, with chromium and nickel as the primary alloying elements.

The 410 martensitic SS, which uses chromium as the main alloying element, performed more poorly than the AISI 4130 low-alloy steel in the cavitation test.

Galling Tests

The results of the galling tests appear in Table 10. Figure 5 shows typical examples of the two modes of failure: gall and seize. The alloy test combinations are categorized in accordance with their failure modes and coefficients of friction in Table 11.

These tests indicate that the Falex friction and wear tester can provide both qualitative and quantitative results on the relative adhesive wear resistance of materials combinations. This test, which determines adhesive wear resistance under dynamic conditions, more nearly simulates wear ring service than the quasi-

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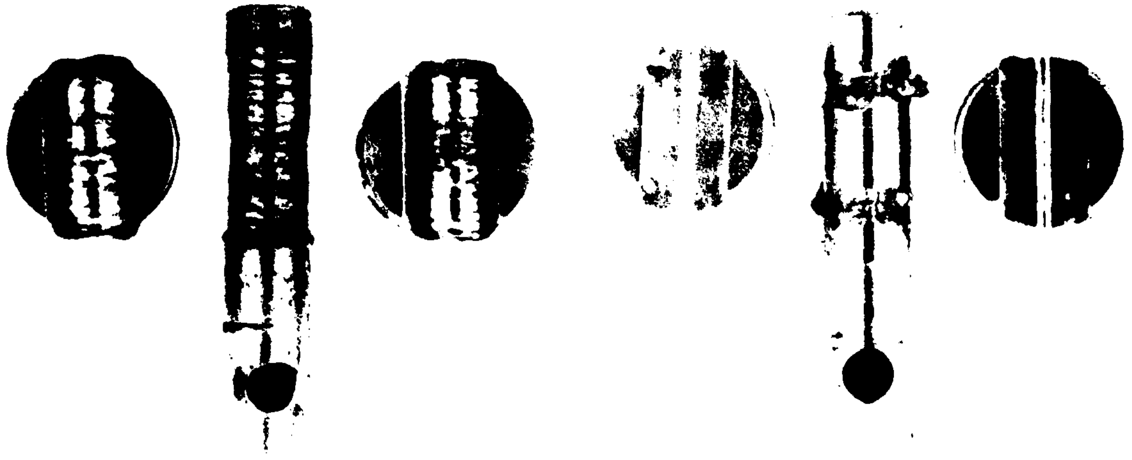
[5] *Armco Nitronic 60 Stainless Steel,* Armco Steel Corporation Product Data Sheet S-56a (Armco, October 1976).

Table 9
Ranking of Alloys in Accordance with Cavitation Resistance*

Ranking	Alloy Designation	Brinell Hardness No.	Erosion Rate (in./yr)
1	Armco N60	201	0.4
2	Carpenter 455 (heat treated)	418	0.9
3	Armco 17-4 PH (heat treated)	388	1.2
4	Carpenter Custom 450 (heat treated)	320	1.3
5	Armco PH 13-8 Mo	331	1.5
6	Armco PH 13-8 Mo (heat treated)	444	1.5
7	Armco 17-4 PH	321	1.6
8	304 austenitic SS	197	1.7
9	Carpenter Custom 450	270	1.9
10	4130 low alloy steel	286	2.5
11	410 martensitic SS	223	3.8

*Metric conversion: 1 in./yr = 24.5 mm/yr.



Nitronic 60
Stainless Steel
Test No. 1

410
Stainless Steel
Test No. 1

Figure 5. Photographs of gall test specimens showing failure modes (gall on left and seize on right).

Table 10
Gall Tests Results*

Test Combinations							
Journal Alloy Designation	Vee Blocks Alloy Designation	Test Duration (min)	Direct Load (lb)	Maximum Torque (in-lb)	Coefficient of Friction	Failure Mode	Remarks
304 austenitic SS	304 austenitic SS	5.8	350	55	0.47	Gall	
304 austenitic SS	410 martensitic SS	7.7	500	476	0.30	Gall	
304 austenitic SS	Carpenter 450	11.0	600	54	0.27	Gall	
304 austenitic SS	Armco N60	0.1	250	55	0.65	Seizure	Failed during run-in period, duplicate tests
304 austenitic SS	4130 low alloy steel	0.02	200	55	0.82	Seizure	Failed during run-in period
410 martensitic SS	410 martensitic SS	0.02	200	55	0.82	Seizure	Failed during run-in period, duplicate tests
410 martensitic SS	Armco N60	0.02	200	55	0.82	Seizure	Failed during run-in period
Carpenter 450 SS	Carpenter 450 SS	0.03	250	55	0.65	Seizure	Failed during run-in period, duplicate tests
Carpenter 450 (heat treated)	Carpenter 450 (heat treated)	19.0	1000	52	0.26	Gall	
Carpenter 455 (heat treated)	Carpenter 455 (heat treated)	9.8	550	55	0.30	Gall	
Carpenter 455 (heat treated)	Armco N60	11.9	600	54	0.27	Gall	
Armco 17-4 PH SS	Armco 17-4 PH	0.02	200	55	0.82	Seizure	Failed during run-in period, duplicate tests
Armco 17-4 PH SS	304 austenitic SS	8.3	485	48	0.29	Gall	
Armco 17-4 PH SS	Armco 17-4 PH (heat treated)	3.5	200	55	0.82	Seizure	
Armco 17-4 PH SS	Armco N60	0.06	250	55	0.65	Seizure	Failed during run-in period, duplicate tests
Armco 17-4 PH (heat treated)	Armco 17-4 PH (heat treated)	0.1	200	55	0.82	Seizure	Failed during run-in period
Armco 17-4 PH (heat treated)	Armco 17-4 PH SS	0.08	200	55	0.82	Seizure	Failed during run-in period
Armco PH 13-8 Mo	Armco PH 13-8 Mo	0.04	200	55	0.82	Seizure	Failed during run-in period
Armco PH 13-8 Mo (heat treated)	Armco PH 13-8 Mo (heat treated)	19.0	1000	53	0.24	Gall	
Armco N60	Armco N60	13.5	750	55	0.22	Gall	
Armco N60	304 austenitic SS	4.2	300	55	gall		
Armco N60	410 martensitic SS	0.02	200	55	0.82	Seizure	Failed during run-in period
Armco N60	Carpenter 450 SS	12.0	700	55	0.23	Gall	
Armco N60	Armco 17-4 PH SS	5.8	350	55	0.48	Gall	
Armco N60	4130 low alloy steel	14.6	800	55	0.20	Gall	
4130 low alloy steel	4130 low alloy steel	0.3	200	55	0.82	Seizure	Failed during run-in period

***Metric conversions**: 1 lb = 0.453 kg; 1 in.-1 lb = 1.1298×10^{-1} Nm.

Table 11
Relationship of Failure Mode to Coefficient of Friction

Journal Alloy Designation	Vee Blocks Alloy Designation	Failure Mode	Coefficient of Friction
Armco N60	4130 low alloy steel	Gall	0.20
Armco N60	Armco N60	Gall	0.22
Armco N60	Carpenter 450 SS	Gall	0.23
Armco PH 13-8 Mo (heat treated)	Armco 13-8 Mo (heat treated)	Gall	0.24
Carpenter 450 (heat treated)	Carpenter 450 (heat treated)	Gall	0.26
304 austenitic SS	Carpenter 450	Gall	0.27
Carpenter 455 (heat treated)	Armco N60	Gall	0.27
Armco 17-4 PH SS	304 austenitic SS	Gall	0.29
304 austenitic SS	410 martensitic SS	Gall	0.30
Carpenter 455 (heat treated)	Carpenter 455 (heat treated)	Gall	0.30
304 austenitic SS	304 austenitic SS	Gall	0.47
Armco N60	Armco 17-4 PH SS	Gall	0.47
304 austenitic SS	Armco N60	Seizure	0.65
Carpenter 450 SS	Carpenter 450 SS	Seizure	0.65
Armco 17-4 PH SS	Armco N60	Seizure	0.65
4130 low alloy steel	4130 low alloy steel	Seizure	0.82
410 martensitic SS	410 martensitic SS	Seizure	0.82
410 martensitic SS	Armco N60	Seizure	0.82
431 martensitic SS	Armco N60	Seizure	0.82
304 austenitic SS	4130 low alloy steel	Seizure	0.82
Armco 17-4 PH SS	Armco 17-4 PH SS	Seizure	0.82
Armco 17-4 PH SS	Armco 17-4 PH (heat treated)	Seizure	0.82
Armco 17-4 PH (heat treated)	Armco 17-4 PH (heat treated)	Seizure	0.82
Armco 17-4 PH (heat treated)	Armco 17-4 PH SS	Seizure	0.82
Armco N60	410 martensitic SS	Seizure	0.82
Armco PH 13-8 Mo	Armco PH 13-8 Mo	Seizure	0.82

static test conducted by industry.[6] Qualitative results can be obtained by comparing the modes of failure; quantitative comparisons can be made by using the values of the friction coefficient generated.

The galling tests revealed:

1. A strong relationship between coefficients of friction (calculated for test combinations and mode of failure).

2. Coefficients of friction for couples failing by the gall mode of between 0.22 and 0.55.

3. Coefficients of friction for test couples failing by the seizure mode of more than 0.65.

Dynamic Fracture Toughness Tests

Table 12 summarizes the Dynamic Fracture Toughnesses (K_{ID}) of the steels. The N50 and 410 steels exhibited the lowest toughness at room temperature. Average values are only reported for steels where more than one value of K_{ID} was determined.

Fastener Selection Parameters

Table 13 summarizes the properties of the steels investigated. Improper heat treatment of the precipitation hardenable steels can result in the loss of high strength, corrosion resistance, and resistance to SCC. Optimum properties result from the H1150 ± 15°F (±−9°C) treatment for Custom 450, 17-4 PH, and PH

Table 12
Dynamic Fracture Toughness Test Results

Alloy Designation	K_{ID} (ksi-in.$^{1/2}$)*		
	22°C	0°C	−51°C
AISI 304 SS	92.8		
	115.8	96.4	125.0
	Average = 104.3	Average = NA	Average = NA
AISI 410 SS	82.3	105.4	
	81.7	85.0	117.8
	Average = 82.0	Average = 95.2	Average = NA
Carpenter 455	102.2	96.0	
	139.7	99.8	149.4
	Average = 121.0	Average = 97.9	Average = NA
Armco 17-4 PH	96.9		
	97.2	NA	118.3
	Average = 97.1		Average = NA
Armco PH 13-8 Mo	91.9	140.5	
	112.0	116.6	188.2
	Average = 102.0	Average = 128.3	Average = NA
Armco N50	68.7	144.0	
	85.4	102.0	145.6
	94.0	118.4	138.0
	Average = 82.7	Average = 121.5	Average = 141.8
Armco N60	100.9	98.1	
	106.9	92.8	166.4
	103.1	149.2	116.9
	Average = 103.7	Average = 113.4	Average = 141.7

*Metric conversion: 1 ksi-in.$^{1/2}$ = 9.1×10^{-7} Pa-m$^{1/2}$
NA = not applicable.

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[6] W. J. Schumacher, "New Galling Data Aid in Selecting Stainless Steels," *Materials Engineering* (April 1973).

Table 13
Fastener Selection Guide*

Steel Designation	AISI 304	AISI 410	Carpenter 450	Carpenter 455	Armco 17-4 PH	Armco PH 13-8 Mo	Armco N50	Armco N60
1. Condition	Annealed + 10% CW	Annealed	H1150	H1050	H1150	H1150	Annealed	Annealed
2. UTS (ksi)	99	144	143	190	125	145	120	104
3. 0.2% YS (ksi)	66	77	93	175	85	105	60	59
4. Elongation, in % in 2 in.	47	25	23	15	22	20	50	60
5. Hardness, Rockwell "C", or Brinell	B197 (21.7R_c)	B223 (23.8R_c)	33.4R_c	43.3R_c	32.6R_c	33.1R_c	B98 (26.4R_c)	B212 (21.4R_c)
6. Charpy V, ft-lb (room temp)	110	24	96	35	100	Very high	170	240
7. Susceptibility to chloride pitting, % reduction in passive region	39	100	79	85	76	89	0	21
8. Galvanic corrosion current couple with A36, A/cm²	2.0×10^{-5}	2.5×10^{-5}	1.6×10^{-5}	2.3×10^{-5}	1.9×10^{-5}	1.9×10^{-5}	2.2×10^{-5}	1.4×10^{-5}
9. Δv (potential difference vs A36)	0.246	0.086	0.212	0.212	0.190	0.202	0.281	0.247
10. Cavitation corrosion rate (in./yr)	1.7	3.8	1.9	0.9	1.6	1.5		0.4
11. Galling susceptibility (coefficient of friction)**	0.47	0.82	0.26	0.3	0.82	0.24		0.22
12. K_{ID} (average dynamic fracture toughness), ksi-in$^{1/2}$								
(a) 22°C	104.3	82.0	NA	121.0	97.0	102.0	82.7	103.6
(b) 0°C	96.4	95.2	NA	97.9	NA	128.6	121.5	113.4
(c) −51°C	NA	NA	NA	NA	NA	NA	141.8	141.7
13. Sensitivity to improper heat treatment	None	Yes, avoid 700–1050°F	Yes, avoid 600–950°F, specify H1150 ± 15°F	Yes, specify H1050 ± 15°F	Yes, avoid 600–900°F, specify H1150 ± 15°F	Yes, specify H1150 ± 15°F	None	None

Table 13 (continued)

Steel Designation	AISI 304	AISI 410	Carpenter 450	Carpenter 455	Armco 17-4 PH	Armco PH 13-8 Mo	Armco N50	Armco N60
14. Sensitivity to SCC in aqueous chloride-containing environments having >500 ppm NaCl	No	Yes	Yes	Yes	Yes	Yes	No	No
15. 10^7 cycles endurance limit (fatigue) (ksi)	34	40	80	82	87	100	NA	NA
16. Machinability (AISI B1112 Steel = 100%)	75	54	45	45	45	45	NA	NA
17. Weldability	VG+	F	G	G	G	VG	G	G
18. Typical properties	Good corrosion resistance, low strength	High strength, marginal corrosion resistance, sensitive to SCC	Moderate strength, good corrosion resistance, sensitive to improper heat treatment	High strength, good corrosion resistance, sensitive to improper heat treatment and SCC. Not recommended for aqueous environments	Moderate strength, good corrosion resistance, sensitive to improper heat treatment	High strength, good corrosion resistance, sensitive to improper heat treatment and SCC. Not recommended for aqueous environments	Pitting resistant, corrosion resistant, moderate strength, resistant to chlorides	Gall resistant low strength good corrosion resistance
19. Typical CW applications	Seal plates and bars, guide bars, and low-strength fasteners	Plates only (no fasteners)	Hardened gate rollers and track plates, submerged piston rods and high-strength fasteners	Machine parts requiring high strength which are subject to atmospheric corrosion, i.e., piston rods	Hardened gate rollers and track plates, submerged piston rods and high-strength fasteners	Machine parts requiring high strength which are subject to atmospheric corrosion, i.e., fasteners	Same applications as 304 SS where Cl-corrosion erosion pitting resistance is needed	Where galling can occur, such as pins for gate roller chains and metal slide gate seals
20. Cost (July 81 for 2000 lb of 1-in. bar) $/lb	1.83	1.57	2.06	4.14	2.06	5.97	3.04	2.62

*Metric conversions: 1 in. = 25.4 mm; 1 lb = 0.453 kg; 1 ft-lb = 1.35 N-m; 1 A/cm² = 0.01 A/mm²; (F-32) × 0.55 = °C; 1 ksi-in.$^{1/2}$ = 9.1×10^{-7} Pa-m$^{1/2}$

**The susceptibility to galling increases as the coefficient of friction increases

+VG = very good, G = good; F = fair, NA = not available

13-8 Mo; and H1050 ± 15°F (± 9°C) treatment for Custom 455. Thus, only these heat treatments are specified in Table 13.

Table 13 also lists the ultimate tensile strength (UTS), 0.2 percent offset yield stress (0.2 percent YS), percent elongation in 2 in. (50 mm),* and Charpy V-Notch toughness in foot-pounds. The 304 SS used in this investigation was a 1-in. (24.5-mm) bar which was 10 percent cold worked; thus, it had relatively high strength (99 ksi [683 MN/m^2]). It should be noted that in 304 SS thicker than a 5-cm (50-mm) diameter, cold working can increase strength to only about 40 ksi (276 MN/m^2). The N50 is a relatively soft stainless steel which has low strength and high toughness. It has slightly higher strength and lower toughness than N60. The precipitation hardenable steels exhibit high strength, low ductility, and moderate to high toughness. The 410 SS exhibits high strength and the lowest toughness (Charpy V-Notch toughness = 24 ft-lb [32.5 N-m]).

The galvanic corrosion rates of the steels coupled with A36 steel and the potential of the steels vs A36 steel are listed in the seventh and eighth rows of Table 13. The corrosion potentials do not help predict the corrosion rate (i.e., corrosion current), but show that all of the stainless steels are cathodic when electrically coupled to carbon steel structural alloys such as A36 or 4130 in the environments typically encountered in Civil Works applications. The 410 SS/A36 couple exhibited the highest galvanic corrosion current (1.6 mA/cm^2 [0.016 mA/mm^2]), and the N60/A36 couple exhibited the lowest galvanic corrosion current (0.09 mA/cm^2 [0.09 mA/mm^2]). The other steels exhibited galvanic corrosion currents similar to that of 304 SS.

The effect of chloride ions on the anodic potential range where the steels remain passive is shown in the ninth row of Table 13. Under the test conditions, 410 SS exhibited the poorest resistance to chloride ion attack; the passive region was eliminated (i.e., there was a 100 percent reduction in the passive region). The precipitation hardenable steels were moderately sensitive to the chloride ions and 304 SS, N50, and N60 were the least affected by chloride ions. Passive currents in the chloride-containing environments did not exhibit the same trend, but relatively low passive currents were observed for the steels which passivated.

The results of cavitation and galling tests are shown in the tenth and eleventh rows of Table 13. The N60 exhibited superior cavitation and galling resistance; this alloy was designed as a gall-resistant alloy. The 410 SS exhibited both poor cavitation and galling resistance. The other alloys had cavitation resistances similar to that of 304 SS

A summary of the dynamic fracture toughnesses of the steels at three temperatures appears in the twelfth row of Table 13.

The properties of precipitation hardenable alloys may be adversely affected by improper heat treatment; the ranges of treatment temperatures that can cause loss of desirable properties are listed in the thirteenth row of Table 13. These alloys are also sensitive to SCC resulting from improper heat treatment. The 410 SS is highly susceptible to SCC; the other steels are low-strength alloys which do not suffer from SCC, except in very aggressive environments.

The costs of the steels (July 1981 quotes for 2000 lb [907 kg] of 1-in. [24.5-mm] bars) are tabulated in the last row of Table 13. Costs ranged from $1.57 to $5.97/lb ($3.46 to $13.19/kg).

Summary

From Table 13 it is evident that:

1. The 410 SS should not be used for fasteners in aqueous environments, but may be used for applications such as plates where low stresses and mildly corrosive environments are encountered.

2. The 304 SS is recommended for use as a corrosion resistant material where low stresses are encountered, such as gate seal plates.

3. The N50 is recommended for low-strength applications where resistance to pitting attack by chlorides is desired.

4. The N60 exhibits good corrosion resistance and is suggested for use as an antigalling material at relatively low to moderate stresses. Other steels having corrosion resistances similar to 304 SS should be used where higher strengths are necessary.

5. The 17-4 PH and Custom 450 are recommended for use in aqueous environments such as bolts in pumps and turbines where both high strength and corrosion resistance are required. However, it is necessary to

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*Elongation in percent in 2 in. (50 mm) hardness is the Brinell or Rockwell scale (R_b or R_c).

specify the H1150 ± 15°F (±9°C) heat treatments for these materials to avoid lowered strength and susceptibility to SCC.

6. The PH 13-8 Mo and Custom 455 are recommended for use in air for high strength applications such as piston rods. These steels have very high strengths; consequently, they are susceptible to SCC and recommended for use *only* in air. They are also expensive and this may also preclude their use. Conditions H1050 ±15°F (±−9°C) for Custom 455 and H1150 ±15°F (±−9°C) for PH 13-8 Mo should be specified if they are used.

5 CONCLUSION

This report presents the results of an investigation into the mechanical properties, corrosion resistance, and cost of eight wrought stainless steels with the potential for use in Civil Works applications.

It was concluded that no single stainless steel can offer optimum performance under all conditions. However, the design engineer can use the Fastener Selection Guide (Table 13) developed during this study to select wrought stainless steels for specific Civil Works applications. For site-specific problems in selecting materials contact the Office of the Chief of Engineers (DAEN-CWE-E).

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APPENDIX A:
PROPERTIES, METALLURGY, AND MODES OF CORROSION OF STAINLESS STEELS

Stainless Steels

Steels having varied corrosion resistance and mechanical properties are available today in many shapes and sizes. The selection of steels to fit a particular application requires a basic understanding of the metallurgy and properties of available steels.

Stainless steels are defined as steels having a minimum of 10 to 12 percent chromium, which gives them improved corrosion resistance properties. Few of these steels contain less than 50 percent iron or more than 30 percent chromium. These alloys are available in wrought or cast form; castings are available in all of the grades used for wrought steels as well as other specialized grades not available for wrought grades. This is because wrought grades must have sufficient ductility to allow for cold and hot working, while the cast forms need not be subjected to this constraint.

Stainless steels are classified based on compositional, microstructural, and crystallographic factors as ferritic, martensitic, austenitic, or precipitation-hardenable. These steels are based on the iron-chromium system; adding different elements to this system can greatly affect the structure and properties of the resulting alloys. These effects can be considered by observing what happens when various elements are added to the iron-chromium binary phase diagram shown in Figure A1.[7] The ferrite, or alpha, iron is shown in Figure A1 as α. This phase has a body-centered cubic structure and can contain as much as 0.02 percent carbon in solid solution. The austenite, or gamma (γ), iron shown in Figure A1 has a face-centered cubic structure and may contain as much as 2.0 percent carbon in solid solution. Martensite is not shown in Figure A1; it is a nonequilibrium phase consisting of a body-centered tetragonal iron with carbon in supersaturated solid solution.

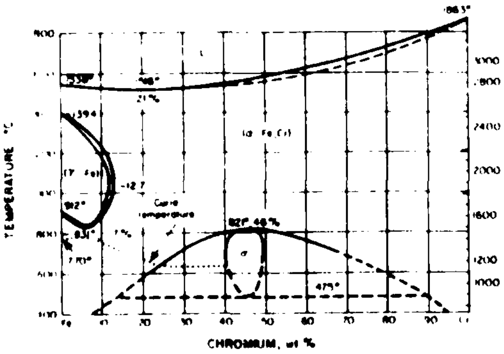

Figure A1. The Fe-Cr phase diagram.

In general, stainless steels are more ductile and tougher than carbon steels. Strength and hardness may be increased by cold work of ferritic and austenitic types and by heat treatment of precipitation hardening and martensitic grades. Also, some ferritic grades can be hardened slightly by heat treatment.

Ferritic Grades

Ferritic grades of steel are defined as those that contain at least 10 percent chromium and that have microstructures of ferrite plus carbides. Figure A1 shows regions of stability of the alpha ferrite phase and the gamma phases in the Fe-Cr system. The alpha ferrite phase is extensive while the gamma phase is closed within a loop. When the chromium content exceeds 13 percent chromium, alpha ferrite is the only stable phase. However, if carbon is present, it will react with chromium to form chromium carbide, thus depriving the matrix of chromium. As a result, some ferritic steels contain extra chromium to ensure that the chromium content of the matrix exceeds 13 percent. Ferritic grades have the advantage over unalloyed ferrites of higher corrosion resistance.[8]

Martensitic Grades

Martensitic grades of steel are magnetic iron-chromium steels that may or may not contain small additions of other alloying elements. These steels usually contain no more than 14 percent chromium and an amount of carbon sufficient to promote hardening. If they contain other elements, their total concentration is usually no more than 2 to 3 percent. They are ferritic in the annealed state, but martensitic after quenching from above their critical temperature. These alloys were developed to provide a group of steels which are corrosion resistant and hardenable by heat treatment. These properties are obtained by adding carbon to the Fe-Cr system. This enlarges the gamma-loop (see Figure A1) and makes possible martensite transformation

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[7] D. Peckner and I. M. Bernstein, *Handbook of Stainless Steels*, edited by H. B. Crawford and B. Gatewood (McGraw-Hill Book Co. 1977), Chapter 1.

[8] D. Peckner and I. M. Bernstein, *Handbook of Stainless Steels*, edited by H. B. Crawford and B. Gatewood (McGraw-Hill Book Co. 1977), pp 1-2 to 1-4.

from austenite. This occurs in a manner similar to that of carbon steels when martensitic steels are subjected to a quench temperature cycle. Martensitic steels can be strengthened and hardened by heat treatment to strengths as high as 270,000 psi (1862 MN/m^2), but these alloys are not as corrosion resistant as the ferritic or austenitic grades.[9]

Austenitic Grades

Austenitic steels are nonmagnetic iron and chromium alloys which have been sufficiently alloyed with nickel or manganese and nitrogen to have an austenitic structure at room temperature. Austenitic stainless steels are formed by the addition of a face-centered cubic element such as nickel or manganese to the iron-chromium system (see Figure A1). This results in an enlargement of the gamma loop and in the enhancement and enlargement of the gamma phase (austenite). For example, alloying iron chromium steels with at least 8 percent nickel suppresses the formation of alpha ferrite giving a stable austenitic structure at room temperature. Austenite is nonmagnetic as compared with martensitic and ferrite steels.

The most common austenitic alloys are iron-chromium-nickel steels commonly referred to as the 300 series. These steels are very corrosion resistant because of their high chromium and nickel content, but give up strength for corrosion resistance. They cannot be hardened by heat treatment as austenite is the only stable phase, but they can be hardened by cold working. The type 200 grades of stainless steels are those in which manganese has been substituted for part of the nickel. Free carbon is held to a minimum in austenitic steels by adding titanium or niobium (columbium). This avoids the formation of grain boundary carbide precipitates which can cause intergranular attack and loss of toughness. Some 300 grades contain chromium contents up to 26 percent and nickel contents up to 22 percent giving them very good corrosion resistance. Other steels in the 300 series, such as 316 SS, contain molybdenum, which improves the alloys' resistance to pitting in chloride solutions.[10]

Precipitation Hardenable Grades

Precipitation hardenable stainless steels are heat treated to their desired properties by the fabricator and fall into three general families: austenitic, semi-austenitic, and martensitic.[11]

The martensitic types have compositions chosen so that martensite forms on cooling from elevated temperatures between about 250 and 100°F (121 and 38°C). These steels are based on 18 Cr-8 Ni austenitic composition with small additions of carbon and a slight decrease in nickel, chromium, and manganese contents. During initial cooling of the steel from the range of 1850 to 1950°F (1008 to 1063°C), soft martensite is formed. The steels are then aged at 900 to 1200°F (482 to 648°C). This precipitates compounds of nickel with aluminum, titanium, and niobium; complex carbides may also form during the aging process.

The semiaustenitic grades have M_s (the martensitic transformation temperature) below room temperature. The steels develop a face-centered cubic structure on cooling from a solution-annealed state. In this state, they are relatively soft, ductile, and workable. The steels are then strengthened by reheating, quenching to form martensite, and finally reheating to precipitate compounds in a multistep process. The semiaustenitic types have strengths 10 to 15 percent higher than the martensite types.

The austenitic types of precipitation hardenable steels are basically 300 series stainless steels made with increased amounts of nickel, aluminum, and titanium to yield precipitates. Both the maximum and yield strengths of these steels are lower than those of other grades, but they may be used to higher temperatures; the heat treatment of the austenitic grade is performed at about 1300°F (704°C), compared to a nominal 900°F (482°C) for martensitic and semiaustenitic grades.

Generally, the precipitation hardenable alloys may be classified as single- or double-treatment alloys. Alloys such as Custom 450, Custom 455, 17-4 PH, and 15-5 PH are solution-annealed at about 1900°F (1040°C) to dissolve the hardening agent. The structure transforms to martensite on cooling to room temperature, leaving the alloy supersaturated with the hardening element. A single heat treatment at 900 to 1150°F (480 to 620°C) is all that is needed to precipitate the second phase that strengthens the steel. Double-treatment alloys such as 17-7 PH require subsequent heat treatments to obtain the desired properties.

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[9] D. Peckner and I. M. Bernstein, *Handbook of Stainless Steels*, edited by H. B. Crawford and B. Gatewood (McGraw-Hill Book Co. 1977), pp 1-4 to 1-6.

[10] D. Peckner and I. M. Bernstein, *Handbook of Stainless Steels*, edited by H. B. Crawford and B. Gatewood (McGraw-Hill Book Co. 1977), pp 1-6 to 1-7.

[11] D. Peckner, pp 1-7 to 1-10.

Precipitation hardenable steels can be hardened without a great loss of corrosion resistance, an advantage over other grades of steels. Stainless steels in the 300 series cannot be heat treated and give up strength for corrosion resistance. The 400 series of precipitation hardenable steels can be strengthened by heat treatment, but exhibit a lowered corrosion resistance.

Corrosion of Stainless Steels

The corrosion resistance of stainless steel results from the formation of a protective hydrous oxide film on the steel's surface under oxidizing conditions. This condition is called passivity. The film forms only in certain environments under certain conditions and different steels exhibit various ranges of passivity.

Stainless steels would dissolve rapidly when in direct contact with a corrodent without the presence and maintenance of the inert, passive film. This is because the metal itself does not have good corrosion resistance. Thus, the corrosion resistance of stainless steels is usually either very good or very poor; intermediate corrosion resistance is seldom observed. Increased corrosion rates occur when the passive film becomes unstable or localized attack occurs.

Many factors can have deleterious effects on the corrosion resistance and mechanical properties of stainless steels. Cold work sometimes reduces the corrosion resistance of stainless steels; this effect is rather specific and depends on many factors such as composition and the extent and uniformity of cold work. Improper heat treatment can also reduce the corrosion resistance of steels and there can be a subsequent loss of mechanical properties. Surface condition, system design and fabrication, and environment can also have a pronounced effect on the performance of stainless steels.

The Effect of Composition on Passivity

Stainless steels derive their corrosion resistance from the presence of chromium; corrosion resistance increases as the chromium content increases. However, a passive film will only form on grades of steels containing at least 10 percent chromium. Nickel in high-chromium stainless steels improves resistance to some nonoxygenating media, but nickel is usually added to impart properties other than corrosion resistance. Manganese is an effective austenite stabilizer that does not increase corrosion resistance. Molybdenum improves the resistance of stainless steels to halogen salts and to pitting in seawater by strengthening the passive film in environments where it is normally likely to fail. However, if pitting of the steel occurs, corrosion will be as severe as that of steels which do not contain molybdenum.

Heat Treatment and Welding

Various heat treatments can have a pronounced effect on the corrosion resistance of stainless steels. Stainless steels exhibit higher corrosion resistance when all of the carbon is in solid solution in a homogeneous, single-phase alloy. Unstabilized austenitic alloys become susceptible to intergranular attack at room temperature in many environments if they are heated to a temperature between 1000 and 1550°F (550 and 1000°C). This heat treatment precipitates chromium carbide from the matrix, leaving behind regions near the grain boundaries which are depleted in chromium. These regions of low chromium concentration are then subject to accelerated attack. This process is called sensitization. Intergranular attack caused by carbide precipitation can be minimized by decreasing the carbon content of an unstabilized austenitic alloy.

The time at the sensitizing temperature also has an effect on corrosion resistance. At elevated temperatures, carbides precipitate rapidly at grain boundaries. Welding stainless steels can sensitize regions near the weld without affecting either the weld or base metal. In general, the degree of sensitization induced by welding increases as the heat input per unit length of weld increases. Low heat input techniques such as arc welding at high travel speeds are used to minimize sensitization. Oxyfuel-gas welding is seldom used for welding stainless steels because of both the high heat input and the strong possibility of carburization of the stainless steel. Although sensitization does not adversely affect the mechanical properties of stainless steels, subsequent intergranular attack may have detrimental effects on the steel's ability to sustain a load in a corrosive environment.

Martensitic stainless steels normally exhibit maximum corrosion resistance in the fully hardened condition; they must be properly heat treated to give maximum corrosion resistance. These steels are usually tempered to reduce quenching stresses at or below 700°F (375°C), where ductility and toughness are improved without adversely affecting corrosion resistance. Martensitic steels should not be tempered between 700 and 1050°F (375 and 500°C), as both lowered corrosion resistance and toughness will result. This phenomenon is known as temper embrittlement.

Ferritic grades of stainless steels may lose their corrosion resistance following some heat treatments. Usually, after welding, nonhardening ferritic steels containing from 10 to 29 percent chromium are annealed to maximize corrosion resistance and ductility in the regions near welds.

Precipitation hardenable steels as previously indicated derive their strength and corrosion resistance from heat treatment. The properties of these alloys are very dependent on heat treatment and some alloys require complex heat treatment processes. For example, semiaustenitic precipitation hardenable steels require several heat treatment cycles while martensitic types require only a simple aging treatment.

Modes of Corrosion of Stainless Steels

Stainless steels may experience many forms of attack in corrosive environments: intergranular attack, pitting, creviceing, galvanic corrosion, concentration cell corrosion, stress corrosion cracking, corrosion fatigue, and uniform corrosion. Stainless steels do not usually exhibit intermediate corrosion properties; they usually are very corrosion resistant or poorly corrosion resistant.

Intergranular Attack

Intergranular corrosion usually results when stainless steels are sensitized by improper heat treatment. Unstabilized austenitic steels containing more than 0.03 percent chromium are susceptible to sensitization when complex chromium carbides precipitate. Various tests may be used to detect the susceptibility of steels to intergranular attack[12] and techniques are available to eliminate chromium carbide precipitation in stainless steels.[13] Intergranular corrosion resulting from sensitized stainless steels is now well understood and guarded against; the incidence of this type of failure is very low.

Pitting and Crevice Corrosion

Pitting of stainless steels is a localized form of corrosion which occurs when the passive film for some reason is unable to restore passivity. Rapid dissolution of the film at the point of initiation occurs and deep pits may result. These pits can affect both the mechanical and electrochemical integrity of the stainless steels.

Generally, stainless steels are especially prone to pitting in solutions containing appreciable amounts of chlorides. Acid chlorides in higher valence states (such as cupric chloride and ferric chloride) are more aggressive than lower valence chlorides, and solutions containing solutions of other halides (iodide and bromide ions) and sulfates also cause pitting of stainless steels. Pitting can be a source of trouble whenever stainless steels are used in chloride-containing environments; the resistance of stainless steels to pitting may be increased by adding molybdenum.

Crevices at joints and connections, and points of contact between metals, are often attacked. Crevice corrosion also can occur on stainless steels under barnacles in seawater or at regions of the steel where corrosive solutions stagnate. The passive oxide film on stainless steel may not heal after being disrupted in a crevice where limited oxygen is available. This results in a "differential oxygen cell," where the region in the crevice corrodes rapidly. This situation is often compounded when corrosive solutions such as seawater or moisture are trapped within the crevice. Furthermore, crevices often stay damp longer than surrounding areas. Gasket materials containing sulfur or graphite often aggravate crevice corrosion.

A double electrolytic effect occurs if the oxygen concentration in a crevice falls below that needed to keep the anodic area passive. Corrosion accelerates because both a differential oxygen cell and a high potential difference develops between the active anode and cathode. Chlorides often assist this kind of attack, which can lead to severe pitting. Solutions in a crevice become more aggressive than the bulk solution and may become very acidic; solution pH in a crevice as low as 1.2 is possible.

It is difficult to evaluate the susceptibility of various steels to pitting and crevice corrosion; test reproducibility is often poor and instances of failure are intermittent. For this reason, an evaluation of the pitting or crevice corrosion potential of steels is often both qualitative and somewhat subjective. The susceptibilities of some steels to pitting and crevice corrosion are:[14]

1. Highly susceptible: 200 series, 400 series, and Type 303

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[12] *Standard Recommended Practices for Detecting Susceptibility to Intergranular Attack in Stainless Steels*, ANSI/ASTM 4262-79 (ASTM, 1977).

[13] *Metals Handbook*, Ninth Edition, Vol. 3, "Properties and Selection of Stainless Steels, Tool Materials and Special Purpose Metals" (American Society for Metals, 1980), pp 3-40.

[14] D. Peckner and I. M. Bernstein, *Handbook of Stainless Steels*, edited by H. B. Crawford and B. Gatewood (McGraw-Hill Book Co 1977), Chapter 2.

2. Somewhat susceptible: 300 series (not 303) and the precipitation-hardenable grades, with Type 316 or 316L decidedly superior

3. Slightly susceptible: Carpenter 20Cb3

Stainless steels containing molybdenum and high chromium contents are best suited for use in seawater where crevicing may occur and efforts to prevent solution stagnation are usually made. The presence of molybdenum in Type 316 and Carpenter 20Cb3 is thought to be an important factor in corrosion resistance, but once a pit or crevice is initiated, corrosion occurs as rapidly as in other stainless steels.[15]

Galvanic and Concentration Cell Corrosion

Galvanic and concentration cell corrosion are forms of uniform corrosion affected by: the conductivity of the corrosion circuit, the potential between the anode and the cathode, polarization, relative areas of anode and cathode, geometrical factors between dissimilar metal surfaces, and contact between metals. One of the most important of these factors is the relative areas of the active anode and cathode; the existence of a large cathode and small anode will cause an increased current density (i.e., corrosion rate) at anodic regions. For example, carbon steel is usually anodic when coupled to stainless steel; carbon steel bolts in a stainless steel plate will corrode at an accelerated rate while stainless steel bolts in a carbon steel plate will cause only a small increase in the corrosion rate of the carbon steel. However, in a few instances it is also poor practice to couple stainless bolts with a carbon steel structure.

Stainless steels usually do not corrode much in humid environments, but other metals such as carbon steel, low alloy steel, cast iron, and zinc may corrode faster if coupled with stainless steel. However, it has been reported that bronze, brass, copper, graphite, and cast iron may be coupled with Type 304 austenitic SS without adverse effects on their corrosion properties.[16]

Stress-Corrosion Cracking and Corrosion Fatigue

The Stress Intensity Factor. The nominal stress applied to a material is intensified near a crack or flaw and many metals will crack under stress in various environments when the applied stress is relatively low. Corrosion cracks are generally brittle on the microscopic scale; i.e., they occur before the onset of general yielding, while the bulk material is still in an elastic state. For this reason, linear elastic fracture mechanics is used to describe SCC in metals too ductile to measure mechanical fracture toughness by fracture mechanics methods.

When a metal is stressed in a manner which tends to open and extend an existing crack, the applied stress is intensified near the crack tip. The stress intensity at the crack tip is quantified by using the stress intensity factor, K, which has units of ksi $(\sqrt{\text{in}})$ or $\text{MNm}^{-3/2}$. The stress intensity factor is generally defined as:

$$K^2 = \frac{1.2\pi\sigma^2 a}{\psi^2 - 0.212\dfrac{\sigma^2}{\sigma_y}} \qquad \text{[Eq A1]}$$

where:

a is the depth of the crack

σ is the stress

σ_y is the yield strength

ψ is a shape factor.

Various shape factors are used depending on test configuration. If the length of a crack is 2b, then ψ^2 has the values for various crack shapes listed in Table A1. Equation A1 may be simplified by assuming the existence of a yield point stress and a long thin crack, giving:

$$a_{cr} = 0.2\left(\frac{K_{Iscc}}{\sigma y}\right)^2 \qquad \text{[Eq A2]}$$

where:

σy is the yield strength

a_{cr} is the critical crack length

K_{Iscc} is the stress intensity factor for SCC.

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[15] T. J. Lennox, M. H. Peterson, and R. E. Groove, *Marine Corrosion Studies: The Corrosion Characteristics and Response to Cathodic Protection of Several Stainless Steel Alloys in Quiescent Sea Water* (Sixth Interim Report on Progress), NRL Memorandum Report 1948 (Naval Research Laboratory [NRL], November 1968).

[16] *Metals Handbook*, Ninth Edition, "Properties and Selection of Stainless Steels, Tool Materials and Special Purpose Metals" (American Society for Metals, 1980), pp 62-63.

Table A1
Values of ψ^2

$\frac{a}{b}$		ψ^2
0	very long, thin crack	1.00
0.25		1.14
0.50		1.46
0.75		1.89
1.0	semicircular crack	2.46

In this case, a_{cr} is the length of a critical crack under an applied stress σy. A crack longer than a_{cr} will grow while one shorter will not. The stress intensity factor or K_{Iscc} also has practical importance. For example, if it is known that cracks below a certain size cannot be detected or removed from a metal, K_{Iscc} may be used to determine the maximum applied stress which a material can withstand without the occurrence of SCC. It is often difficult to interpret the practical significance of published SCC results, but K_{Iscc} can be used to at least qualitatively evaluate the SCC resistance of materials. As K_{Iscc} increases, so does the stress needed to initiate SCC. This factor does not describe the speed at which cracks expand, but is useful in determining the stability of cracks. It should be noted that K_{Iscc} is a function of environment and will be different for the same metal in different corrosive mediums. The plane-strain fracture toughness, K_{Ic}, is used to quantify material toughness in environments which are not corrosive. In general, if K_{Iscc} in a particular environment is below K_{Ic}, the material is susceptible to SCC in that environment. Techniques for obtaining and evaluating data have not been perfected and spurious results often occur.[17]

SCC of Stainless Steels. SCC is caused by both electrochemical and mechanical effects and often results in catastrophic material failure. SCC requires both a corrosive environment and mechanical stresses (either applied or residual). Many mechanisms for this complicated form of attack have been proposed, but for engineering applications, past experience and reliable testing provide the best guide for designing against SCC. The environments that cause SCC are usually specific and cause little or no general attack.[18]

The SCC of steels has recently received much attention and the susceptibility of stainless steels is affected by factors such as alloy composition, temperature, stress level, corrosion potential, surface condition, and anions and cations in corrosive media.[19]

Nickel is the alloying element that has the greatest effect on SCC. Steels which contain 8 percent nickel are more susceptible to SCC than those containing either more or less nickel.[20] To provide stainless steels with SCC immunity, 35 to 45 percent nickel must be added.[21] Chromium in excess of 10 to 15 percent in austenitic stainless steels is considered to be slightly detrimental to SCC properties. The effect of alloying elements and impurities on SCC of stainless steels is not well understood, but very high purity steels exhibit excellent SCC resistance. However, these steels are expensive and difficult to produce on a commercial scale.[22]

The occurrence of SCC is usually associated with high stresses (near the yield stress). But, in severely corrosive environments, stresses as low as 0.1 percent of the yield stress can initiate SCC.[23] This mode of failure is usually not a problem in fresh water at low stress environments. Thermal stress relief of austenitic stainless steels has been used to control SCC.[24] However, stainless steels that have been improperly heat treated can develop undesirable phases that can lower ductility and reduce SCC resistance.

In general, high-strength steels (steels with tensile strengths greater than 180,000 psi [124 110 kPa]) are much more susceptible to SCC than weaker steels. As-drawn or severely cold-worked stainless steels also

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[17] B. F. Brown, "Test Methods and Interpretation of Test Data," *Stress Corrosion Cracking Control Measures* (U. S. Government Printing Office [GPO], 1977).

[18] H. G. Fontana and N. D. Greene, *Corrosion Engineering*, edited by B. J. Clark and F. A. Neal (McGraw-Hill Book Co. 1978), p 386.

[19] E. C. Hoxie, "Some Corrosion Considerations in the Selection of Stainless Steels for Pressure Vessels," *Pressure Vessels and Piping: Decade of Progress*, Vol 3 (American Society of Mechanical Engineers [ASME], 1976).

[20] E. C. Hoxie, *Pressure Vessels and Piping Decade of Progress.*

[21] D. Peckner and I. M. Bernstein, *Handbook of Stainless Steels*, edited by H. B. Crawford and B. Gatewood (McGraw-Hill Book Co. 1977), pp 62–63.

[22] E. C. Hoxie, *Pressure Vessels and Piping Decade of Progress.*

[23] E. C. Hoxie, *Pressure Vessels and Piping Decade of Progress*, and D. Rockner and I. M. Bernstein, *Handbook of Stainless Steels*, pp 62–63.

[24] E. C. Hoxie, *Pressure Vessels and Piping Decade of Progress.*

are more susceptible to SCC than annealed stainless steels, unless the annealed steels are exposed to very high stresses. Ferritic grades of stainless steels are not considered to be susceptible to SCC in chloride environments, but will pit badly. Austenitic grades have been reported to exhibit SCC in chloride-containing solutions when high stresses (residual or applied) were present, and martensitic grades also exhibit SCC when exposed to stress in chloride environments. Recently, interest has developed in the use of high-strength precipitation hardenable steels in marine environments. These steels generally become more susceptible to SCC as hardness increases. Ferritic and high purity ferritic stainless steels are more resistant to SCC than Type 304 SS in chloride-containing environments, but can exhibit SCC in sodium hydroxide in high pressure/high temperature water environments. Sensitization of high purity stainless steels can also lead to SCC susceptibility.

The susceptibility of precipitation hardened steels to SCC increases as strength increases. Armco 17-7 PH and Armco 17-4 averaged at 1150°F (621°C) have been reported to display the greatest resistance to SCC.[25] However, it also is reported that the stress corrosion resistance of semiaustenitic precipitation hardenable stainless steels such as 17-7 PH, PH 15-7 Mo, and AM 355 is generally lower than that of martensitic stainless steels.[26] (Failure of 17-7 PH in the RH 900 and TH 1050 conditions has been reported, but the mechanisms were not identified.) Service performance of the martensitic alloys 17-4 PH (H1000), PH 13-8 Mo, and Custom 455 suggests that these alloys have good stress corrosion resistance.[27]

Corrosion Fatigue of Stainless Steels. Corrosion fatigue is similar to SCC and has led to catastrophic stainless steel failures in corrosive environments where cyclic stresses are encountered. The mechanism(s) of this form of attack has not been established and crack initiation and propagation have been observed to react differently to environmental factors.[28] The fatigue limit of stainless steels is very sensitive to surface condition and the existence of pits can greatly reduce a metal's resistance to cyclic stresses. Adding nickel to stainless steels provides them with the best resistance to corrosion fatigue.

Various tests are used to rate a particular metal's resistance to corrosion fatigue. Usually, resistance limit is defined as the maximum load at which a test piece will survive a test of given duration without failure. In this type of test, the number of loading cycles must be specified for a particular set of data. Both the corrosive environment and surface condition can affect corrosion fatigue data. These data usually cannot be extrapolated to reliably predict metal behavior in environments other than that of the test.[29]

Corrosion fatigue as well as SCC may be designed against by avoiding sharp fillets, high localized strains at load transfer sites, and conditions where pitting of crevicing may cause localized stresses.[30]

Erosion Corrosion and Cavitation

Erosion corrosion is the acceleration in the rate of deterioration of a metal in a corrosive environment caused by the relative motion of a corrosive fluid and metal surface. In general, the motion is rapid and mechanical abrasion of the metal surface is involved. Most metals and alloys are susceptible to erosion corrosion. Metals which depend on passivity for corrosion resistance can be attacked rapidly when the protective surface is damaged or worn. Metal resistance to erosion corrosion generally increases as hardness increases.[31]

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[25] E. C. Hoxie, "Some Corrosion Considerations in the Selection of Stainless Steels for Pressure Vessels," *Pressure Vessels and Piping: Decade of Progress*, Vol 3 (ASME, 1976).

[26] C. S. Carter, D. G. Farwick, A. M. Ross, and J. M. Uchida, "Stress Corrosion Properties of High Strength Precipitation Hardening Stainless Steels," *Corrosion*, Vol 27, No. 5 (May 1971).

[27] C. S. Carter, D. G. Farwick, A. M. Ross, and J. M. Uchida, "Stress Corrosion Properties of High Strength Precipitation Hardening Stainless Steels," *Corrosion*, Vol 27, No. 5 (May 1971); F. S. Jacobson and D. D. Miller, *Preliminary Evaluation of Hydrofoil Base Metals and Coating Systems*, Report No. 173-255 (The Boeing Co. February 1973), and R. W. Judy, Jr., C. T. Fujii, and R. J. Goode, *Properties of 17-4 PH Steel*, NRL Report 7639 (NRL, December 1973).

[28] D. Peckner and I. M. Bernstein, *Handbook of Stainless Steels*, edited by H. B. Crawford and B. Gatewood (McGraw-Hill Book Co. 1977), pp 16–85; L. Colombier and J. Hochman, *Stainless and Heat Resisting Steels* (Edward Arnold Publishers, 1967), pp 64–65; and H. L. Craig, Jr. and T. W. Crooker, *Corrosion Fatigue Technology*, ASTM Special Technical Publication 642 (ASTM, 1978).

[29] L. Colombier and J. Hochman, *Stainless and Heat Resisting Steels* (Edward Arnold Publishers, 1967), p 188.

[30] B. F. Brown, "Stainless Steels (Austenitic and Ferritic)," *Stress Corrosion Cracking Control Measures* (GPO, 1977), Chapter 7, pp 55–68.

[31] H. G. Fontana and N. D. Greene, *Corrosion Engineering*, edited by B. J. Clark and F. A. Neal (McGraw-Hill Book Co 1978), pp 72 and 386.

Cavitation is a special form of erosion corrosion caused by the formation and collapse of vapor bubbles in a liquid near a metal surface.[32] Cavitation results in the formation of cavities or pits on a metal under conditions where high velocity liquid flow and pressure changes are encountered. This phenomenon is attributed to the shock waves associated with the formation of vapor in low pressure zones and its rapid condensation when pressure is increased. The pressure changes are a result of turbulence in the liquid.[33]

The rate of cavitation attack depends on many factors such as temperature and liquid velocity. Cavitation attack increases as temperature increases primarily because vapor pressures increase as temperature increases. Liquid velocity and turbulence greatly affect cavitation; cavitation increases as velocity and turbulence increase. Liquid composition is not a major factor in cavitation corrosion. For example, seawater does not produce worse cavitation than soft freshwater. However, uniform corrosion and other types of corrosion can be aggravated by the composition of the corrosive medium. Austenitic and martensitic steels resist cavitation better than other low alloy stainless steels; adding nickel to stainless steels improves cavitation resistance.[34] The cavitation resistance of a given steel increases as hardness increases and, as a result, proper heat treatment of stainless steels is essential to providing maximum cavitation resistance.

Description of Steels Investigated

The properties of the steels selected for this investigation are summarized in Tables A2 and A3. Table A2 lists nominal compositions and Table A3 lists the ranges of the mechanical properties of the alloys tested.[35]

Type 304 SS[*]

Type 304 SS is the basic 18-8 stainless steel and is more suitable than Type 302 SS when slightly better corrosion resistance is required after welding. It is a nonhardenable material that has good corrosion resistance to various atmospheres, most acids, hot petroleum products, steam and combustion gases. Intergranular corrosion may occur after it is welded or otherwise heated to temperatures between 600 to 1600°F (422 to 862°C). However, its low carbon content minimizes this effect. Several free machining modifications of Type 304 SS are also available. Type 304 SS can be formed to most shapes with little difficulty; however, an anneal should precede and follow each drastic forming operation because of the work-hardening properties of this alloy. It is difficult to machine. This alloy, in light sections, may be soft soldered or welded and is recommended for applications where the final product cannot be annealed after welding. Type 304 SS has the same superior general corrosion resistance as Type 302 SS. Type 304N SS is a nitrogen modification of Type 304 SS that has equal corrosion resistance and superior strength properties for both the annealed and cold-worked conditions. At a given strength level, Type 304N SS exhibits from 10 to 20 percent more ductility than does Type 304 SS. Stainless 18-9LW can replace Type 304 SS or 304N SS for many applications since it has exceptional cold forming characteristics which can eliminate in-process annealing. The stabilized grades, Types 321 and 347, should be used, however, for operations at from 800 to 1600°F (422 to 862°C) where high stress conditions exist under a corrosive and elevated temperature environment, and for items that cannot be annealed after welding. Type 308 SS is a high chromium and nickel modification of Type 304 SS used primarily in welding rods.

Type 304 is available in billet, bar, forging, wire, strip, tube pipe, sheet, and plate form. It is typically used for kitchenware, door bars and kick plates, coffee urns, chemical handling equipment, soda fountain equipment, flashings, hospital equipment, dairies, pharmaceutical and food processing industries, cryogenic applications, and atomic reactor equipment.

Type 410 SS

Type 410 SS is a basic, hardenable, low chromium stainless steel that has a wide range of properties obtainable by heat treatment. However, the nickel content, as with Type 403 SS, is not specified and it has a slightly different chromium compositional range. Because of its low chromium content, this alloy is used for structural applications where the corrosion resistance of the more highly alloyed grades is not required. In general, the corrosion resistance of Type 410 SS is inferior to that of the 300 grades of stainless

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[32] H. G. Fontana and N. D. Greene, *Corrosion Engineering*, edited by B. J. Clark and F. A. Neal (McGraw-Hill Book Co. 1978), p 84.

[33] L. Colombier and J. Hochman, *Stainless and Heat Resistant Steels* (Edward Arnold Publishers, 1962), p 184.

[34] L. Colombier and J. Hochman, *Stainless and Heat Resistant Steels*, pp 184–188.

[35] *Structural Alloys Handbook*, Vol 2, 1980 Edition (Battelle Columbus Laboratories, 1980).

[*] The following material descriptions are adapted from *Structural Alloys Handbook*, Vol 2, 1980 Edition (Battelle Columbus Laboratories, 1980), except for the N60 description and as cited

Table A2
Nominal Compositions of Stainless Steels*

Alloy Designation	Cr	Ni	C	Mn	Si	P	S	Mo	Cu	Cb	Ti	Co	Al	N	V	Fe
304 SS	18.00-20.00	8.00-10.50	0.08 (max)	2.00 (max)	0.45 (max)	0.030 (max)										Balance
410 SS	11.50-13.50	0.50	0.15 (max)	1.00 (max)	1.00 (max)	0.040 (max)	0.030 (max)									Balance
Custom 450	14.50-16.50	5.50-7.00	0.05 (max)	0.50 (max)	0.50 (max)	0.03 (max)	0.03 (max)	0.50-1.00	1.25-1.75	8 × C (min)						Balance
Custom 455	11.75	8.50	0.03	0.25	0.25				2.25		1.20	0.30				Balance
17-4 PH	15.5-17.5	3.00-5.00	0.07 (max)	1.00 (max)	1.00 (max)	0.04 (max)	0.03 (max)		3.00-5.00							Balance
PH 13-8 Mo	12.25-13.25	7.50-8.50	0.05 (max)	0.10 (max)	0.10 (max)	0.010 (max)	0.008 (max)	2.00-2.50					0.90-1.35			Balance
50	20.50-23.50	11.50-13.50	0.06 (max)	4.00-6.00	1.00 (max)	0.040 (max)	0.030 (max)	1.50-3.00		0.10-0.30				0.20-0.40	0.10-0.30	Balance
60*	16.00-18.00	8.00-9.00	0.10 (max)	7.00-9.00	3.50-4.50									0.08-0.18		Balance

Structural Alloys Handbook, Vol. 2, 1980 Edition (Battelle Columbus Laboratories, 1980).

**Manufacturers' specifications

Table A3
Mechanical Properties of Stainless Steel*

			Mechanical Properties					
Alloy	Material Form or Thickness	Condition	Ultimate Strength (ksi)	Tensile Yield Tensile 0.2% (ksi)	Elongation Strength (%)	Reduction in 2 in. (for bars) (%)	Impact Strength of Area Hardness	Charpy V (ft-lb)
304 SS	Bar	Annealed	87	34	57	67	80 R_b	110
		10% CW	98	70	35		10 R_c	
		40% CW	146	135	12		35 R_c	
410 SS	1-in. bar	Annealed	65	35	27	80	80 R_b	
		Temp 1100°F	118	104	22	66	241 BHN	38
		Temp 600°F	181	143	17	62	361 BHN	38
		Temp 300°F	188	148	17	60	388 BHN	42
Custom 450	1-in. bar	Annealed	141	118	13	50	28 R_c	95
		Age 1150°F	141	90	24	70	28 R_c	97
		Age 1000°F	172	169	18	65	39 R_c	51
		Age 900°F	196	187	15	55	45 R_c	20
Custom 455	1-in. bar	Annealed	145	115	14	60	31 R_c	70
		Age 1000°F	205	195	14	55	45 R_c	20
		Age 950°F	230	220	12	50	48 R_c	14
		Age 900°F	245	235	10	45	49 R_c	9
17-4 PH	Bar	Annealed	150	110	10	45		
		H 1150°F	145	125	19	60	33 R_c	50
		H 1075°F	165	150	16	58	36 R_c	40
		H 1025°F	170	165	15	56	38 R_c	35
		H 900°F	200	185	14	54	44 R_c	17
PH 13-8 Mo	Bar	Annealed					363 BHN	
		H 1100°F	170	150	16	60	36 R_c	60
		H 1050°F	190	180	15	55	43 R_c	50
		H 1000°F	215	205	13	50	45 R_c	30
		H 950°F	225	205	12	40	47 R_c	20
N50	Sheet	Annealed	128	86	36	70	21 R_b	170
		60% CR	212	199	5	55	43 R_c	90
N60**	Sheet	Annealed	103	60	60	74	95 R_b	240
		60% CR	240	195	12	48	43 R_c	

**Structural Alloys Handbook*, Vol 2, 1980 Edition (Battelle Columbus Laboratories, 1980).

Metric conversions = 1 ksi = 6.9 Pa; 1 ft-lb = 1.365N-m; 1 in. = 24.5 mm; (°F−32) × 0.55 = °C.

**Manufacturers' specifications.

steel. Although Type 410 SS is fairly easy to machine, it has a tendency to drag in the annealed condition. Where machinability is a major factor, a free machining grade, Type 416 SS, should be used. This alloy may be welded, provided preheat is applied and there is stress relief after the martensitic transformation. Because Type 410 SS has a low alloy content, it is among the least expensive of the stainless steels. Type 410Cb SS is a columbium modification of Type 410 SS. It is easier to heat treat, has higher strength and toughness, has an improved grain size control, and is more ductile at a given strength level. Type 410 SS is characterized by its high silicon content and is used in all wrought forms as well as in sand and investment castings.

Type 410 SS is available in tubing, bar, plate, sheet, forging, casting, and strip forms. It is typically used for high-temperature corrosive environments; shafts; machinery in the chemical, mining, and food processing industries; low-price cutlery; meat hooks; and coal chutes.

Custom 450 SS

Custom 450 SS is a moderately priced, martensitic, age-hardenable stainless steel that has very good corrosion and stress corrosion resistance combined with moderate strength. It is easy to machine, weld, and form in the solution-annealed condition; it also can be age-hardened at a relatively low temperature without distortion. The general corrosion resistance of annealed Custom 450 SS is superior to that of Types 405, 410, 420, 430, 431 440-C and Custom 455 SS, about equal to that of Type 304 SS, but inferior to that of Type 316 SS. The strength of Custom 450 SS is superior to that of Types 316, 304, 430 and 405 SS, about the same as that of Types 410 and 431 SS, but inferior to that of Custom 455, Type 420 and Type 440-C SS.

Custom 450 SS is available in billets, bar, wire, strip, tubing, and casting form. It is typically used for fasteners; valve parts; boat shafting; pump shafts for marine, chemical, and petroleum applications; and ball and rod end bearings.

Custom 455 SS

This precipitation hardening martensitic stainless steel develops exceptionally high strength with good ductility and toughness. It is highly resistant to SCC, is easily fabricated in the annealed condition, and can be heat treated at relatively low temperatures. The overall corrosion resistance of Custom 455 SS is intermediate to Types 410 and 430 SS. It shows excellent oxidation resistance to 1100°F (587°C), but is recommended for service temperatures to only 800°F (422°C). It can be nitrided and shows a dimensional contraction on heat treatment up to 0.0016 in./in. (0.0016 mm/mm). Custom 455 SS is easily forged at from 1650 to 2300°F (890 to 1247°C) and it is readily cold worked when annealed, even though it is martensitic in this condition. It is usually aged for 4 hours at 900 to 1050°F (477 to 560°C). Its toughness and ductility increase and its tensile strength decreases as the aging temperature increases in the range from 900 to 1050°F (477 to 560°C).[36] It can be machined with practices used for other high-strength alloys or with the procedures used for the nickel maraging steels. Custom 455 SS can be welded, without preheat or post heat, by any of the resistance or inert gas shielded processes.

Custom 455 SS is available in billets, bar, wire, strip, and tubing form. It is typically used for high-strength aircraft fasteners, springs, retaining rings, high strength forgings, gears, shafts, and cryogenic products.

17-4 PH SS

The 17-4 PH SS is a precipitation hardening stainless steel capable of high strength and hardness levels after a relatively simple heat treatment procedure. This grade is martensitic and magnetic in both the solution-treated and precipitation-hardened conditions. It is highly resistant to crack propagation, has good transverse properties, and its corrosion resistance is normally superior to the regular martensitic chromium type of stainless steel. Because of the single low-temperature (900 to 1150°F [477 to 614°C]) precipitation hardening heat treatment of this grade, scaling and distortion are virtually eliminated. Thus, it can be finish machined to close tolerances before heat treatment. This alloy withstands atmospheric corrosion better than all conventional hardenable stainless steels (400 series) and is immune to all foodstuffs, sterilizing solutions, most organic chemicals and dyestuffs, and a variety of inorganic chemicals. Its corrosion resistance generally approaches that of Types 302 and 304 SS, yet it maintains high strength at temperatures up to 600°F (312°C). It is not susceptible to hydrogen embrittlement. It resists nitric acid well, halogen acids poorly, and the sulfur acids moderately. The 17-4 PH SS may be hot worked and forged; however, because of its high yield strength, it is seldom cold worked. In the annealed condition, it machines similar to Types 302 and 304 SS. It can be welded by all methods without being preheated. For comparative purposes, the general fabricating characteristics of 17-4 PH SS are similar to those of Types 410 or 431 SS. As with other precipitation hardening stainless steels, a dimensional change occurs upon hardening which varies from 0.0004 to 0.0010 in./in. (0.01016 to 0.0254 mm/mm) of contraction.

The highest strength for 17-4 PH SS is in condition H-900 (aging for 1 hour at 900°F [477°C]). Overaging it for 4 hours at temperatures from 925 to 1150°F (491 to 614°C) lowers tensile strengths and improves ductility and impact resistance.[37] The 17-4 PH SS is available in bar, forgings, billets, tube, wire, strip, and sheet form. It is typically used for valves, motor shafts, propeller shafts, storage tanks, oil field equipment, aircraft fittings, fasteners, roller chain pins, splines, and gears.

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[36] H. G. Fontana and N. D. Greene, *Corrosion Engineering*, edited by B. J. Clark and E. A. Neal (McGraw-Hill Book Co. 1978), p 64.

[37] A. E. Hoenie and D. D. Roach, *New Developments in High-Strength Stainless Steels*, DMIC Report 223 (Defense Metals Information Center, January 3, 1966).

PH 13-8 Mo SS

This is a martensitic precipitation hardening stainless steel that has excellent toughness and good transverse properties. Its general metallurgy is similar to that of PH 15-7 Mo. However, it maintains these properties along with good corrosion resistance in large sections. As with other precipitation hardening stainless steels, PH 13-8 Mo is hardened with a single aging treatment and has a dimensional contractional associated with it that varies from 0.0004 to 0.0012 in./in. (0.0004 to 0.0012 mm/mm), depending on the hardening treatment. This material has excellent forging and welding characteristics. It can be machined if the speeds used are 20 to 30 percent lower than those used for 17-4 PH SS. The corrosion resistance of PH 13-8 Mo SS exceeds that of Types 410 and 431 SS and is about the same as that of 17-4 PH SS; however, it has the highest stress corrosion resistance of any of the hardenable stainless steels. This alloy was developed to provide a martensitic stainless steel free from delta ferrite in which aluminum is used as the hardening agent. It is used in large cross-section parts that require good centerline transverse ductility and yield strength values to 220 ksi (1517 MN/m^2). As with some other precipitation hardening stainless steels, the fracture toughness is good above room temperature, but decreases rapidly at temperatures below 0°F (−18°C).

The PH 13-8 Mo SS may be solution heat treated at 1825°F (936°C), air cooled to room temperature, and aged at 950 to 1100°F (504 to 587°C). The material is considered to be in condition A after solution treating. The ductility and toughness increase and the tensile strength generally decreases as aging temperature increases.[38] The PH 13-8 Mo SS is available in billet, plate, bar, and wire form. It is typically used for forgings, cold headed and machined fasteners, petroleum and chemical applications requiring stress corrosion resistance, nuclear reactor components, aircraft landing gear parts, and high-performance shafting

50 SS

N50 SS, previously called Alloy 22-13-5, is a relatively inexpensive austenitic stainless steel that provides a good combination of corrosion resistance and strength. Its corrosion resistance is greater than that provided by Types 316, 316L and 317 SS, plus it has about twice the yield strength at room temperature. It also has very good mechanical properties at both elevated subzero temperatures. It remains nonmagnetic even after severe cold working. It resists intergranular attack, but is susceptible to SCC in hot chloride environments, as is Type 316 SS. It can be fabricated with procedures similar to those used for the 300 series stainless steels and it is easy to fusion weld. N50 is available in bar, wire, sheet, strip, billets, and extrusion form. It is typically used for high-strength corrosion resistant applications, including pumps, valves, fittings, fasteners, cables, chains, screens, wire cloth, marine hardware, boat shafting, springs, and photographic equipment.

N60 SS

N60 SS is an austenitic stainless steel with corrosion resistance similar to Type 304 SS, but with almost twice the yield strength at room temperature. It resists galling and exhibits good resistance to metal-to-metal abrasive wear. It has good impact strength and oxidation resistance at subzero temperatures. Its good galling resistance up to temperatures of 1400°F (760°C) makes it a candidate for applications such as fastening systems including nuts and bolts. N60 SS is not hardenable by heat treatment and the recommended thermal treatment is annealing at 1950°F (1066°C) followed by rapid cooling. It is available in bar, wire, and forging billets.[39]

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[38] H. G. Fontana and N. D. Greene, *Corrosion Engineering*, edited by B. J. Clark and F. A. Neal (McGraw-Hill Book Co. 1978), p 84.

[39] B. F. Brown, "Stainless Steels (Austenitic and Ferritic)," *Stress Corrosion Cracking Control Measures* (GPO, 1977), Chapter 7.

APPENDIX B:
POTENTIODYNAMIC SCANS OF STAINLESS STEELS

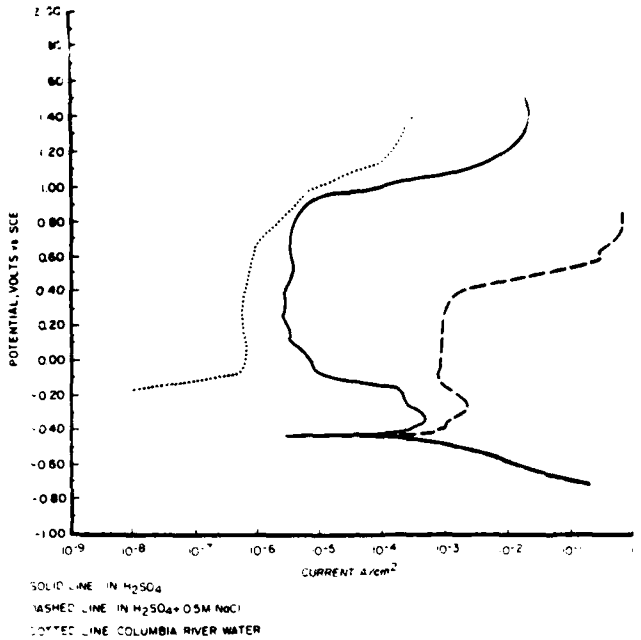

Figure B1. Potentiodynamic scans of 304 SS.

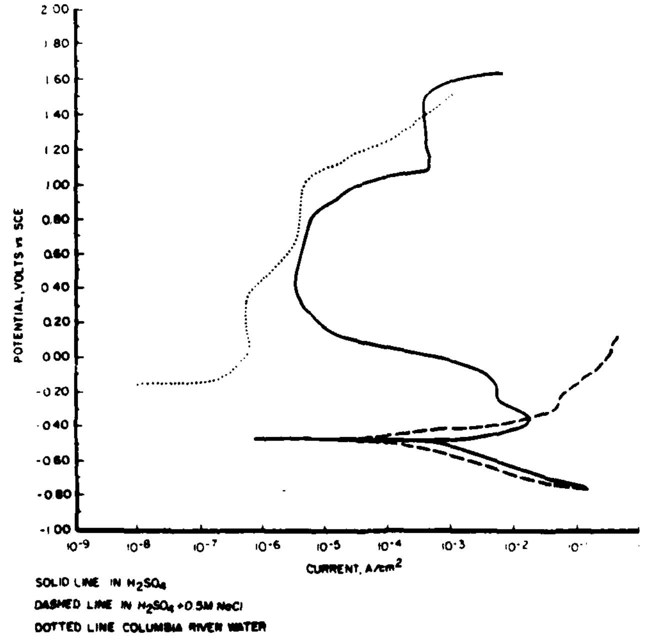

Figure B2. Potentiodynamic scans of 410 SS.

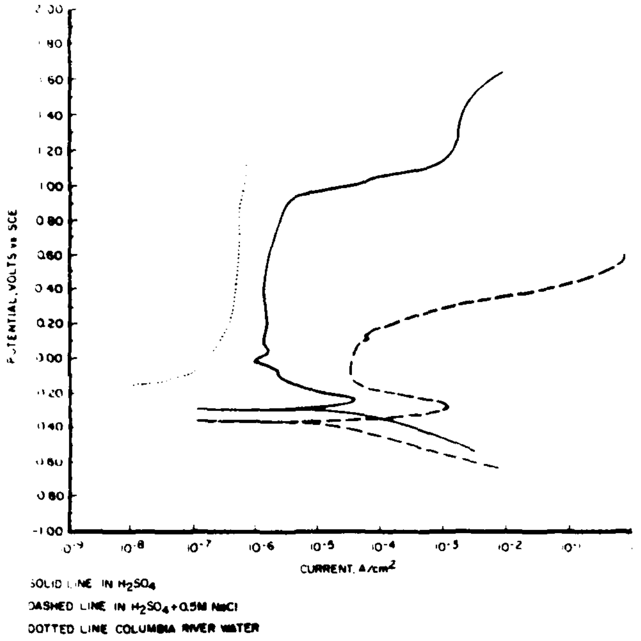

Figure B3. Potentiodynamic scans of Custom 450 SS (ST).

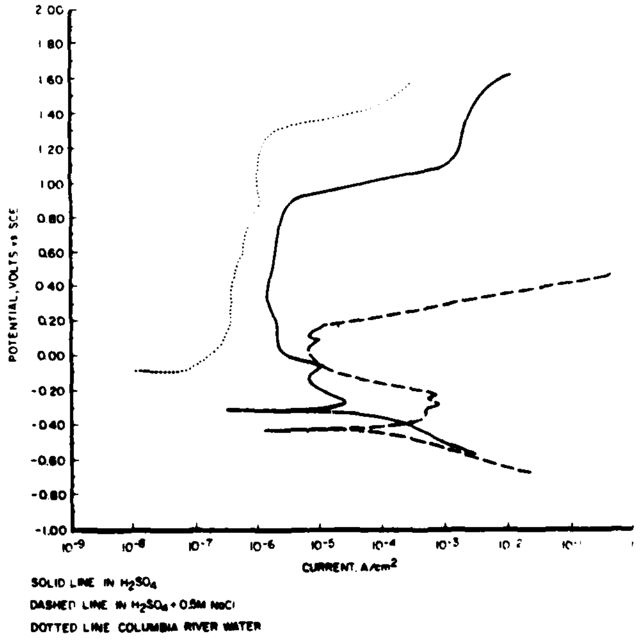

Figure B4. Potentiodynamic scans of Custom 450 SS (H1150).

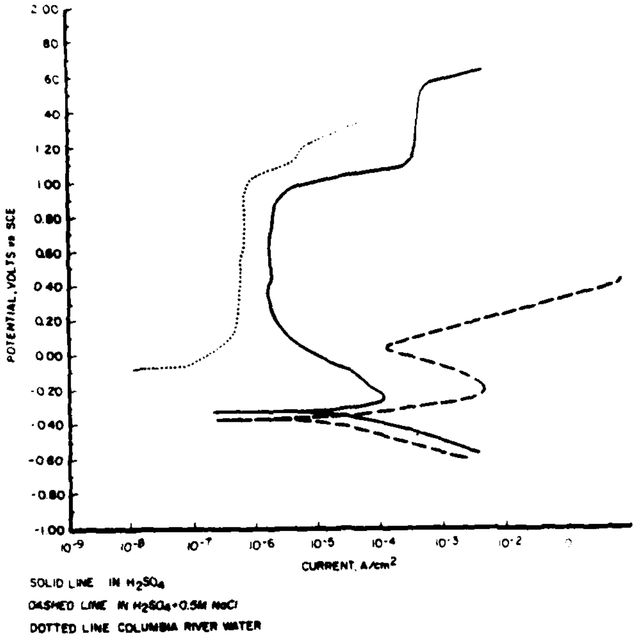

Figure B5. Potentiodynamic scans of Custom 455 SS (ST).

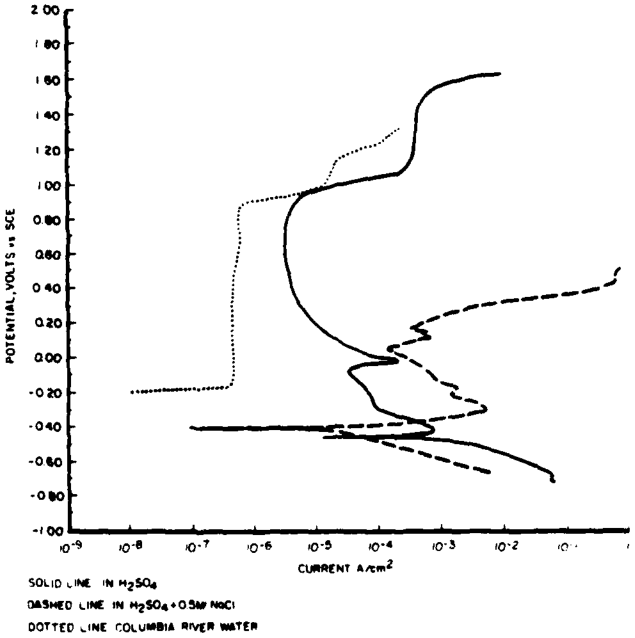

Figure B6. Potentiodynamic scans of Custom 455 SS (H1050).

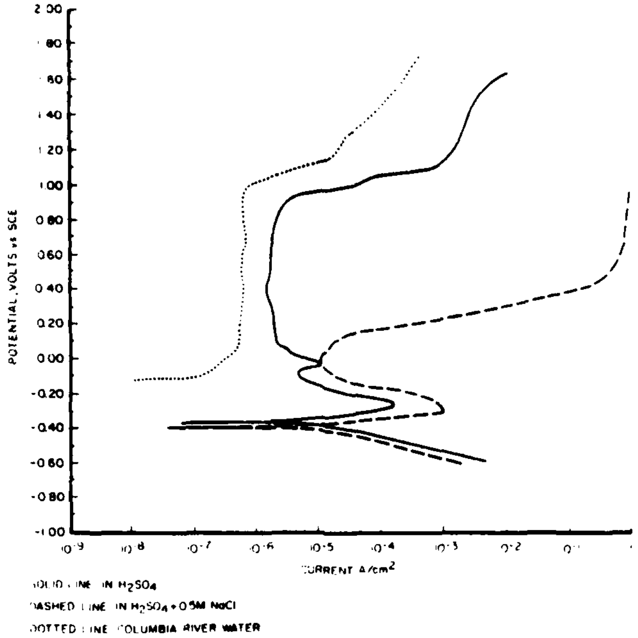

Figure B7. Potentiodynamic scans of 17-4 PH SS (ST).

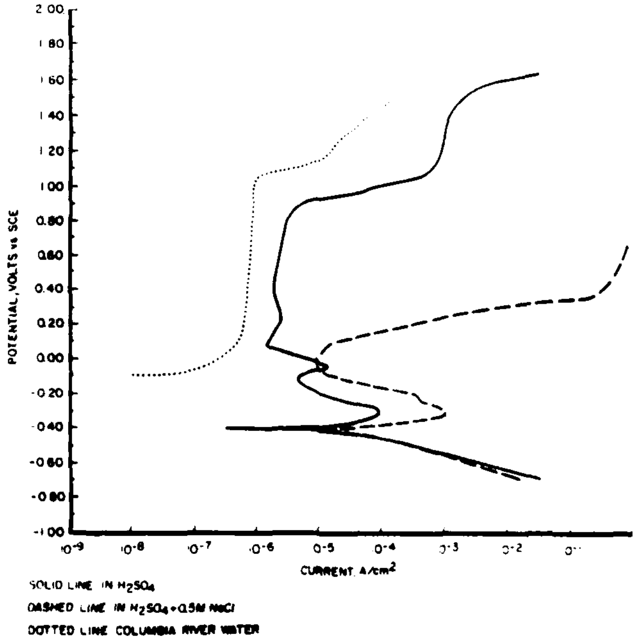

Figure B8. Potentiodynamic scans of 17-4 PH SS (H1150).

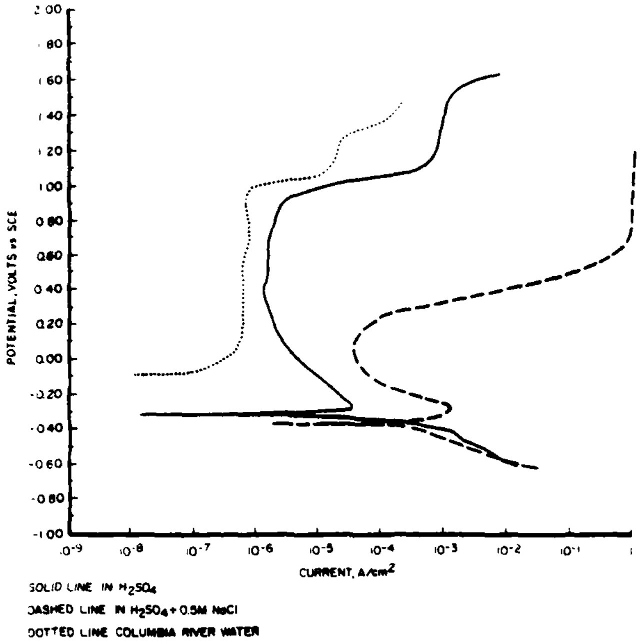

Figure B9. Potentiodynamic scans of PH 13-8 Mo SS (ST).

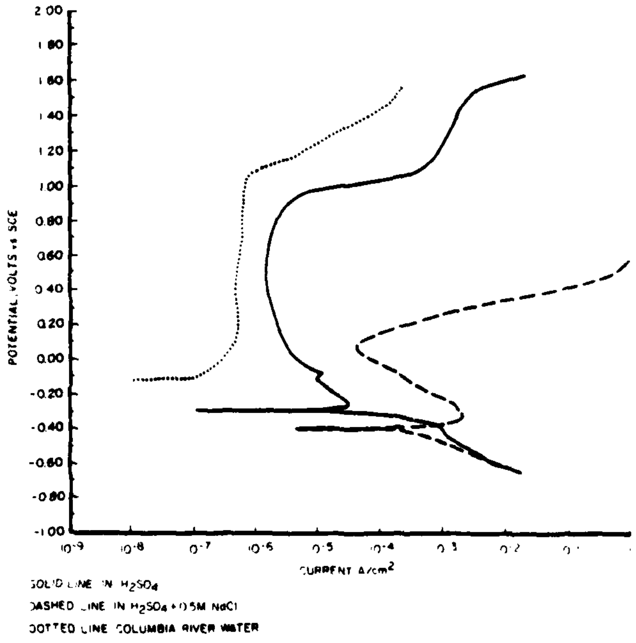

Figure B10. Potentiodynamic scans of PH 13-8 Mo SS (H1150).

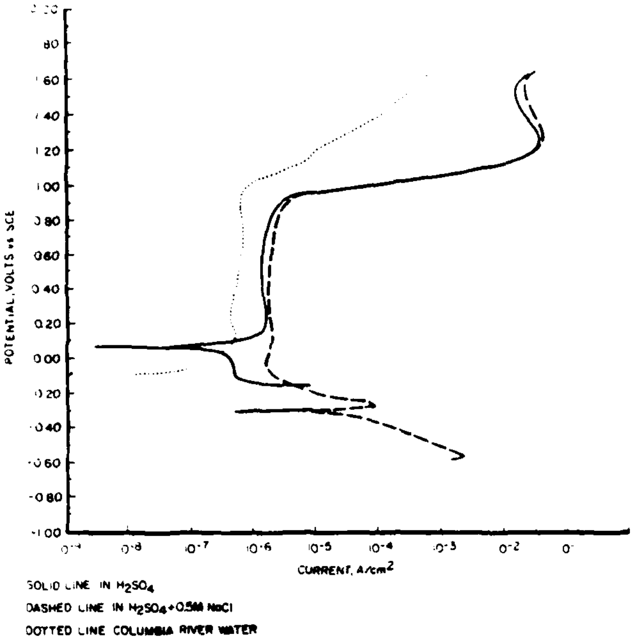

Figure B11. Potentiodynamic scans of N50 SS.

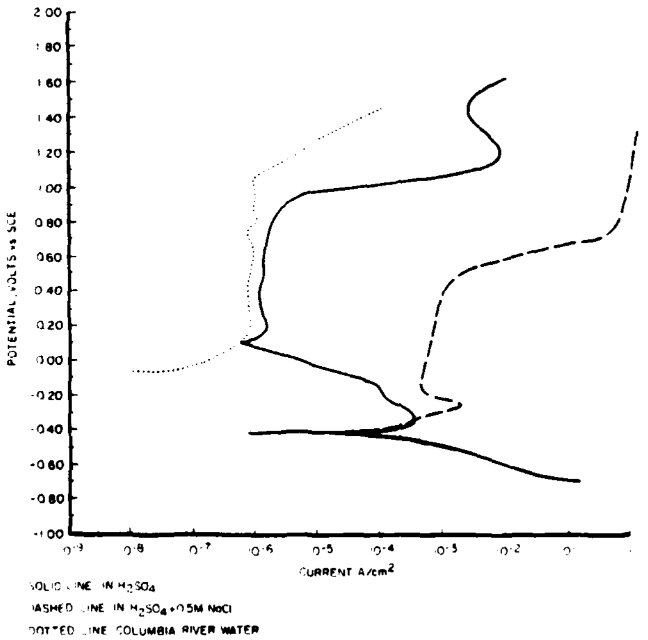

Figure B12. Potentiodynamic scans of N60 SS.

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