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COMPARISON OF U AND Mo IN IMPROVING THE CORROSION RESISTANCE OF AISI 430 STAINLESS STEEL

G.J. BIEFER AND J.G. GARRISON

HOW URANIUM AFFECTS CORROSION OF RESULFURIZED STAINLESSES

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CORROSION FATIGUE OF STRUCTURAL METALS IN MINE SHAFT WATERS

G.J. BIEFER

PHYSICAL METALLURGY DIVISION

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G. J. Biefer and J. G. Garrison Canadian Dept. of Energy, Mines, and Resources, Ottawa, Ontario, Canada

Comparison of U and Mo in Improving the Corrosion Resistance of AISI 430 Stainless Steel

IS URANIUM EQUAL to or better than molybdenum as a means of improving corrosion resistance of AISI Type 430 stainless steel? Laboratory tests in several different corrosive solutions indicate that in ferritic AISI Type 430 stainless steel, alloying additions of 0.24% and 0.55% U resulted in improvements in corrosion resistance. However, somewhat greater improvements generally occurred with additions of 1.02% and 2.03% Mo.

Unlike the situation with the well-known austenitic and martensitic stainless steel types, there has been comparatively little published on ferritic stainless steels (AISI Types 405, 430 and 446) with respect to their corrosion resistance, particularly in controlled laboratory tests. Reports show that 1% Mo in Type 430 (termed Type 434) has better corrosion resistance than straight Type 430 in car trim and that Mo additions have also brought about improved corrosion resistance for ferritic stainless steels in other service applications.[1-3] Conversely, it has been stated that the beneficial effects of molybdenum observed in austenitic stainless steels do not extend to the nickel-free ferritic stainless steels.[4]

SUMMARY

A comparison of molybdenum and uranium as a means of improving corrosion resistance of ferritic AISI Type 430 stainless steel is shown by laboratory tests.

The laboratory tests to determine whether uranium additions to AISI Type 430 ferritic stainless steels in the optimum range of about 0.25-0.5% were competitive with additions of molybdenum to the same steel type are described as follows.[5,6]

Testing

Procedure

Five steels (compositions shown in Table 1) were prepared as 50-lb aluminum-deoxidized melts in an induction furnace. After forging and rolling to ¼-inch plate, the steels were heat-treated for four hours at 1450 F (790 C) then furnace cooled. The corrosion tests were conducted with flat specimens which had been given standardized surface pretreatment. (Conventional experimental techniques used are described elsewhere.)[7]

Results

The tests were conducted in normal solutions of sulfuric acid, hydrochloric acid, and ferric chloride at 75 F (24 C), 122 F (50 C), and 158 F (70 C). Figures 1-3 show the weight losses in the specimens; every point of these figures is an average of two or three replicates.

The Huey test, conducted in 65% boiling nitric acid, resulted in specimen weight losses in five successive 48-hr exposures. The results are presented in Table 2. Weight losses and surface appearances observed after creviced specimens of the five steels had been exposed to a 3% sodium chloride solution at 122 F (50 C) for one week (previous work had shown that crevice corrosion attack is slow at room temperature) are given in Table 3.

The laboratory tests demonstrated that in AISI Type 430 ferritic stainless steels uranium and molybdenum additions are both capable of producing improved corrosion resistance in aqueous media. Improvements imparted by the Mo additions were somewhat greater than those resulting from the U additions though higher levels of Mo were necessary. An interesting exception to this was observed in tests in ferric chloride at the two higher temperatures where uranium was of some benefit and molybdenum was ineffective.

In conclusion, molybdenum is generally more effective in improving corrosion resistance of AISI Type 430 stainless steel than uranium.

Acknowledgment

The chemical analyses were carried out by the Mineral Sciences Division of the Dept. of Energy, Mines and Resources. Some of the corrosion tests

TABLE 1—Chemical Analyses of Steels

STEEL NO.	PERCENTAGES							
	C	Mn	Si	S	P	Cr	U	Mo
5555	0.13	1.14	0.96	0.019	0.020	17.29	-	-
5556	0.14	1.10	0.93	0.017	0.018	17.29	0.24	-
5557	0.12	1.10	0.91	0.021	0.021	16.95	0.55	-
5801	0.11	1.14	1.02	0.020	0.017	17.64	-	1.03
5802	0.10	1.12	1.03	0.019	0.018	17.55	-	2.03

TABLE 2—Corrosion in Successive 48-Hr Periods in Boiling 65% Nitric Acid (Huey Test)

STEEL NO.	U	Mo	WEIGHT LOSSES, MG/CM²					
			1ST PERIOD	2ND PERIOD	3RD PERIOD	4TH PERIOD	5TH PERIOD	TOTAL, 5 PERIODS
5555	-	-	5.9, 5.8	6.4, 6.2	6.7, 6.6	7.6, 7.0	7.8, 7.6	34.4, 33.2
5556	0.24	-	6.3, 6.2	7.2, 7.4	7.3, 7.0	8.3, 7.6	8.7, 7.7	37.8, 35.9
5557	0.55	-	6.1, 6.0	6.7, 7.1	7.7, 8.2	9.1, 9.8	11.2, 11.5	40.8, 42.6
5801	-	1.02	5.1, 5.2	7.1, 7.2	7.9, 8.8	9.0, 10.2	8.9, 10.6	38.0, 42.0
5802		2.03	112.9, 125.2	- -	- -	- -	- -	- -

were conducted by J. Mar of the Physical Metallurgy Div.

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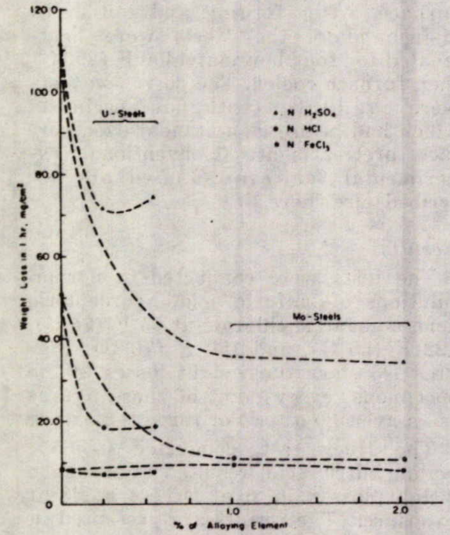


Figure 3—Corrosion of uranium and molybdenum bearing AISI Type 430 stainless steels in normal solutions at 158 F (70 C)

GREGORY J. BIEFER is head of the Corrosion Section of the Physical Metallurgy Division of the Canadian Dept of Energy, Mines, and Resources. He supervises applied and fundamental research and trouble-shooting on corrosion of metals. He graduated with a BSc and PhD in physical chemistry from McGill University, Montreal, Canada. An NACE member, Biefer is also a member of CIC, PIPSC, and ACPO.

JOHN G. GARRISON, technical officer in the Corrosion Section of the Physical Metallurgy Division of the Canadian Dept of Energy, Mines, and Resources, conducts applied and fundamental research and trouble-shooting on corrosion of metals. He attended Dalhousie University, Halifax, Nova Scotia.

TABLE 3—Crevice Corrosion in Oxygenated 3% Sodium Chloride Solution at 122 F (50 C)

STEEL NO.	% U	% Mo	WEIGHT CHANGES AFTER 7 DAYS, mg/cm²	APPEARANCE OF SPECIMEN SURFACES AFTER TEST
5555	-		-2.4, -2.5, -2.4	Dark staining and many pits on all crevice surfaces.
5556	0.24	-	-0.3, -0.3, -0.3	Slight staining and slight pitting on all crevice surfaces.
5557	0.55	-	-0.2, +0.1, -0.4	Slight staining and slight pitting on all crevice surfaces.
5801	-	1.02	+0.1, -0.1, 0	3 out of 6 crevice surfaces essentially unattacked, slight attack on remainder.
5802	-	2.03	+0.1, +0.1, -0.1	5 out of 6 crevice surfaces essentially unattacked, slight attack on one.

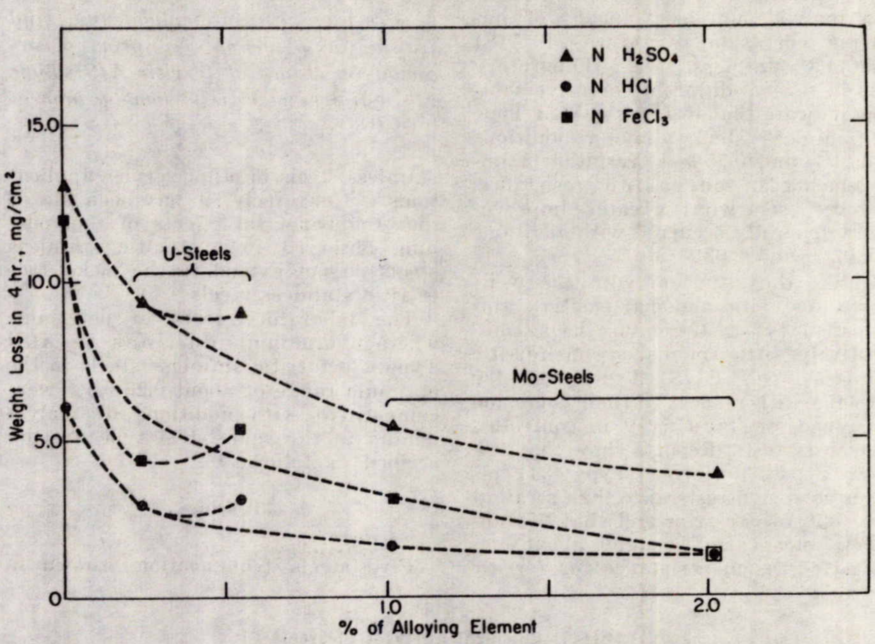


Figure 1—Corrosion of uranium and molybdenum bearing AISI Type 430 stainless steels in normal solutions at room temperature.

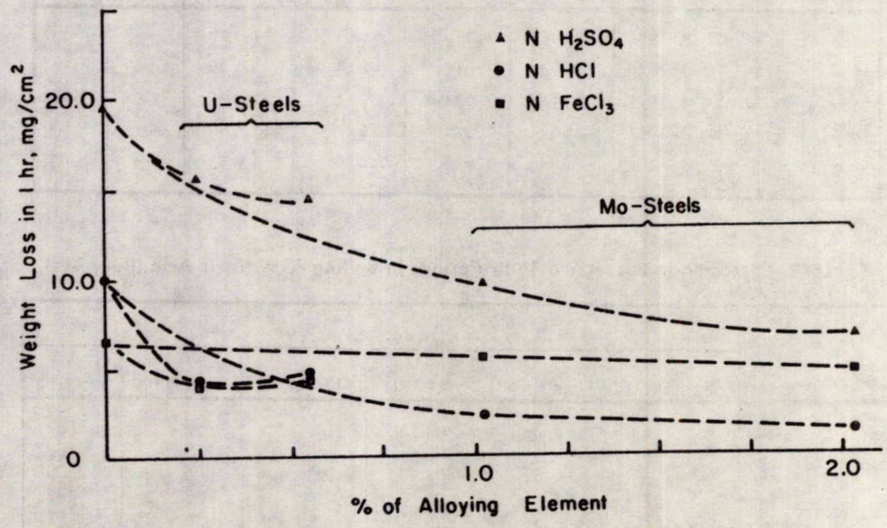


Figure 2—Corrosion of uranium and molybdenum bearing AISI Type 430 stainless steels in normal solutions at 122 F (50 C)

How Uranium Affects Corrosion of Resulfurized Stainlesses

By GREGORY J. BIEFER and WILLIAM M. CRAWFORD

Addition of up to 1.57% U to types 416 and 430F (both resulfurized grades) increases their resistance to nitric acid at room temperature. Alterations in sulfide compositions and shapes (from stringers to globules) are apparently responsible.

Because ferritic stainless steels such as AISI type 430 resist corrosion by nitric acid, they are used widely for chemical processing components. Resulfurization, however, significantly impairs this resistance though it aids machinability.

We have found that this effect can be reversed by adding uranium. With addition of sufficient uranium, sulfides became predominantly globular and retain their shapes through hot rolling. (In marked contrast, sulfide stringers are observed in conventional resulfurized steels.) Furthermore, exploratory research demonstrates that sufficient uranium returns the corrosion resistance lost when sulfur was added.

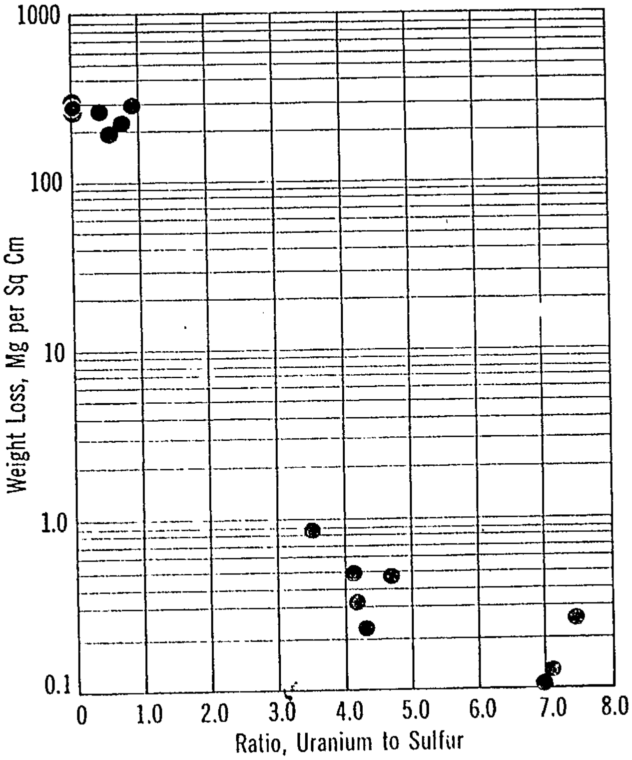
To perform these tests, our technician made eight heats of type 416 (12 to 14% Cr) and eight heats of type 430F (14 to 18% Cr). Four heats in each set contained 0.13 to 0.16% S; four of type 416 had 0.29 to 0.34% S and four of type 430F had 0.11 to 0.23% S. Uranium was added to give nominal uranium to sulfur ratios of 0, 1:1, 4:1 and 7:1. Corrosion tests were carried out on fully annealed steels.

Some Results

Tests in 10% nitric acid at room temperature proved that uranium to sulfur ratios of 3.5:1 or more lowered the corrosion rate strikingly, as shown by Fig. 1. Further tests on the type 430F steels indicated that such steels resisted corrosion by nitric acid in concentrations of 2 to 90%. Figure 2 shows how uranium affects sulfide shapes in the rolled steels. Electrochemical studies indicate that uranium additions affect corrosion behavior in nitric acid (though not in other media) by altering the anodic polarization behavior.

As yet, the composition of the inclusions in uranium-bearing steels has not been determined, though work is proceeding in this direction. Aside from its theoretical interest, it appears that uranium additions to resulfurized stainlesses may enable the production of free-machining steels with good corrosion resistance to nitric acid. Because of the altered morphology of the sulfides, the rolled steels

Fig. 1 — Resulfurized stainlesses containing extra uranium display excellent resistance to nitric acid. Tests in 10% HNO_3 at room temperature lasted 4 hr.



Dr. Biefer is head, Corrosion Section, and Mr. Crawford is scientific officer, Ferrous Metals Section, Physical Metallurgy Div., Mines Branch, Department of Mines and Technical Surveys, Ottawa, Ont.

should also exhibit improved transverse mechanical properties.

Though we have not ascertained the machinabilities of these uranium-treated stainless steels, tests in parallel work on resulfurized carbon steels showed that uranium-bearing steels were equivalent to conventional ones. Clearly, further work in this area is needed.

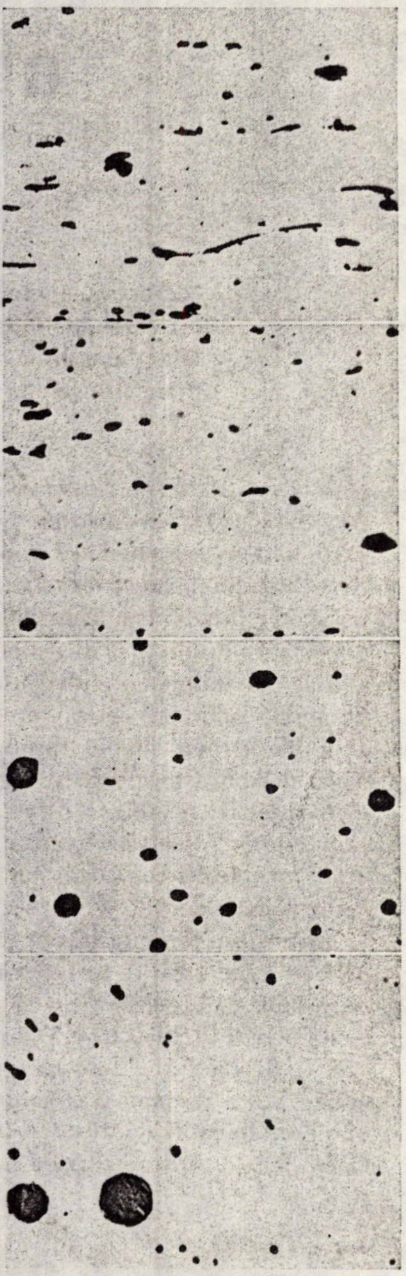


Fig. 2 — The addition of uranium to AISI type 416 containing 0.29 to 0.34% S changes the shapes of the inclusions. Reading top to bottom, uranium to sulfur ratios are 0, 0.7:1, 3.5:1 and 4.7:1. Inclusions in the uranium-bearing steels remain round throughout rolling.

G. J. Biefer

Head, Corrosion Section,
Physical Metallurgy Division,
Mines Branch,
Dept. of Energy, Mines & Resources,
Ottawa, Ont.

Corrosion Fatigue of Structural Metals in Mine Shaft Waters

Transactions, Volume LXX, 1967, pp. 167-173

ABSTRACT

Fatigue and corrosion fatigue measurements were carried out on five commercially available metals — four steels and an aluminum alloy — which are used as structural materials in mine shaft conveyances. In the corrosion fatigue measurements, drain waters collected in the shafts of three different Canadian mines were used as corrodents. The mine waters had been selected on the basis of their relatively large differences in acidity and/or composition.

It was found that the corrosion fatigue strengths of the four steels were similar, despite their differences in tensile properties, and that the type of water used in the tests had little effect on the results. Mild steel showed the highest and most consistent values of the damage ratio (ratio between the corrosion fatigue and the plain fatigue strengths at 10^7 cycles).

The corrosion fatigue behaviour of the aluminum alloy (ASTM Type 6061-T6) was found to differ markedly in the three mine waters. A high damage ratio (i.e., superior performance) was shown in a mine water in which the corrosion attack was uniform; much lower damage ratios were shown in waters which produced localized corrosion attack. Corrosion rates were too low to be determined conveniently by conventional weight-loss methods, but calculations from polarization curves provided a rapid demonstration that corrosion rates were distinctly lower in the mine water which produced high damage ratios.

Introduction

UNDER normal operating conditions, the load-supporting members of mine shaft conveyances, such as skips and cages, are subjected to periodic changes in stress as a result of stopping and starting, loading and unloading. At the same time, the conveyances are subject to corrosion; e.g., by waters draining from the surface or from the walls of the mine shaft. The combined action of fatigue and corrosion, i.e., corrosion fatigue, is suspected to be a factor in a number of cases where the load-supporting members of conveyances have failed, with resulting damage to equipment, interruption of production, and sometimes loss of life (1, 2).

Because very little information is available on the corrosion fatigue resistance of structural metals used in Canadian mines, it was decided to initiate studies in this area. The primary object was to provide basic information which could be used to estimate the resistance to corrosion fatigue of load-bearing members of mine shaft and other comparable conveyances. The most important results of the investigation are discussed in the present report; additional details are reported in references (3) and (4).

Experimental

Metals

The following five metals were selected for the corrosion fatigue studies and were obtained as ¼-in. x 48-in. x 120-in. plates through normal commercial channels.

(a) "T-1" Steel — The United States Steel Corporation
(b) "Abrasive-Resistant" Steel — The Steel Company of Canada Limited
(c) Mild Steel (ASTM Grade A-7) —
(d) "Stelcoloy-G" Alloy —
(e) ASTM 6061-T6 (Alcan 65S-T6)* aluminum alloy — Aluminum Company of Canada Limited.

Compositions and mechanical properties of these metals are listed in Tables I and II.

Mine Waters

Small specimens of mine shaft water were obtained from thirteen representative Ontario mines for detailed analysis by the Industrial Waters Section, Mines Branch. Three mine waters showing markedly differing combinations of acidity and composition, and hence, presumably, different corrosivity, were then selected for the corrosion fatigue measurements. Larger quantities of each of these waters, from the mines listed below, were obtained for use in the tests.

(a) Levack Nickel Mine (International Nickel Co. of Canada), Levack, Ontario, drip from No. 2 shaft
(b) Helen Iron Ore Mine (Algoma Ore Properties), Wawa, Ontario, from No. 5 shaft, 1,600 ft below collar.
(c) Leitch Gold Mines Ltd., Beardmore, Ontario, water collected in a ring 2,863 ft below the surface.

The analyses of the batches of water from these three mines which were used in the tests appear in Table III.

Apparatus and Techniques

Fatigue and Corrosion Fatigue Tests

The corrosion fatigue tests were carried out on a Krouse Reverse-Bend Plate Fatigue Testing Machine having a maximum load of 150 lbs on the connecting rod, operating at a rate of 1,725 cycles/minute. For each specimen, a bent-beam formula was used to calculate the maximum stress encountered in the gauge length during the cycling.

The fatigue specimens were machined so that their 8½-in. lengths lay in the rolling direction, and all flat surfaces were given a fine machine finish. In plain fatigue tests, the specimens were completely coated with lanolin, to prevent atmospheric corrosion

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*Canadian Standards Association (CSA) HA.4 GS11N T-6.

Table I—Analyses of Structural Metals Used

Element	Metal				
	"T - 1" Steel	"Abrasive Resistant" Steel	Mild Steel	"Stelcoloy G" Steel	ASTM 6061 - T6 Aluminum
Al	0.05	0.03	< 0.01	0.03	Base
As	—	—	—	—	—
C	0.16*	0.33*	0.25*	0.23*	—
Co	< 0.01	0.04	0.03	—	—
Cr	0.55	< 0.01	< 0.01	1.05	0.22
Cu	0.28*	0.10*	0.15*	0.40	0.15
Fe	Base	Base	Base	Base	0.40
Mg	—	—	—	—	0.90
Mn	0.67	1.10	0.40	0.40	0.30
Mo	0.60	0.03	< 0.01	—	—
Ni	0.73	0.03	0.06	0.60	—
P	0.016*	0.016*	0.007*	0.015*	—
S	0.029*	0.024*	0.028*	0.031*	—
Si	0.23	0.29	0.02	0.3	0.4
Sn	0.017	< 0.001	< 0.001	—	—
Ti	0.01	< 0.004	< 0.004	—	—
V	0.04	< 0.007	< 0.007	—	—
Zr	0.08	< 0.01	< 0.01	< 0.001	—

*Chemical analysis. Remainder: semi-quantitative spectroscopic analysis

attack. In corrosion fatigue tests, the specimens, after installation in the Krouse tester, were thoroughly degreased using acetone or ethanol. The bottom and sides of the specimen were then coated with lanolin, as was all of the upper surface except a ½-in.-wide strip. At high stresses, where the lanolin flowed over the bare strip because of a rise in specimen temperature during the tests, plasticene dams were constructed at the edges of the bare strip to prevent this flow.

During corrosion fatigue tests, the pertinent mine water was dripped onto the bare strip of metal at a low rate (2-5 drops per minute) by gravity feed from a reservoir containing 2-4 litres, and was found to form an adherent, although agitated, pool on the rapidly cycling specimens. Specimens showing incomplete wetting on the strip, due to improper cleaning, were discarded. Specimens showing complete wetting almost invariably showed breaks which were partly or completely on the wetted strips. Results obtained with specimens of the aluminum alloy in Helen mine water were abnormal in this regard and will be discussed later.

Corrosion Tests

In the case of the ASTM 6061-T6 aluminum alloy, but not the steels, short-term corrosion tests were carried out. Prior to the tests, the rectangular specimens were ground to a uniform finish on water-cooled 120-grit silicon carbide paper lubricated with soap. They were then rinsed thoroughly in tap water, degreased in ultrasonically agitated carbon tetrachloride, dried in hot air, then measured with a micrometer and the total exposed area calculated. This was approximately 18 cm². The specimens were then weighed on an analytical balance with an accuracy of ±0.1 mg.

Table II—Mechanical Properties of Structural Metals Used

Metal	Mechanical Properties			
	UTS, psi	Y.S., 0.2% Offset, psi	Elong., %	Rockwell C Hardness
"T-1" Steel	165,500	151,600	10.3	37
"Abrasive Resistant" Steel	103,100	69,100	25.0	17
Mild Steel	70,900	46,900	31.0	− 3
"Stelcoloy G" Steel	82,900	46,800	27.8	6
ASTM 6061-T6 Aluminum	45,800	42,300	18.5	—

The tests were carried out on three identical aluminum alloy specimens simultaneously, each specimen being alternately dipped for 5 minutes into a pyrex beaker containing 200 ml of one of the mine waters, removed for five seconds, and then re-immersed. This process was continued during a total test duration of 24 hrs, using a fresh batch of mine water for each test. In all, three tests were carried out in each of the mine waters.

Polarization Measurements

A number of workers have shown that corrosion rates of metals in natural and process waters may be determined by means of polarization measurements. In the present investigation, the corrosion rates of ASTM 6061-T6 aluminum alloy in each of the three mine waters were measured using the equations and methods developed by Stern and co-workers (5, 6).

The equipment, which is described in more detail elsewhere (4), consisted of a glass vessel in which each aluminum alloy specimen was immersed in the pertinent water. Provision was made for the flow of electrical current from a platinum auxiliary electrode to the aluminum specimen, and for the measurement of the electrochemical potential of the latter with respect to a saturated calomel electrode. Prior to the measurements, aluminum alloy specimens were given the same surface treatment as that described previously for the specimens given corrosion tests.

After immersion in the mine water for a period of one hour, repeated rapid polarization scans were carried out. In all cases, these started at potentials 100 mV more active (more cathodic) than the rest potential, and a potentiostat (Anotrol Model 4100) was used to sweep the potential in the noble (less cathodic) direction at a linear rate of 1.8 v/hr. A potentiometric chart recorder (Westronics, Model 511 A/U) was used to record continuously the current flowing through the aluminum alloy specimen during the change of potential.

In each of the three mine waters, eight consecutive scans were carried out on each of two specimens. These measurements yielded values of the average "polarization resistance" R_p, which is obtained from the linear slope of the polarization curve $\triangle E/\triangle I$ near the corrosion potential. R_p may be related to the corrosion rate I_{corr} (expressed as an electrical current of dissolving ions) by means of the equation developed by Stern and co-workers:

$$R_p = \frac{B_a B_c}{2.3(B_a + B_c)I_{corr}}$$

B_a and B_c are, respectively, the anodic and cathodic "Tafel" constants, which can be either evaluated experimentally, or, in some cases, deduced from a knowledge of the corroding system. It is claimed that this method can be used to estimate corrosion rates within a factor of 2 for most corroding systems, and that some knowledge of the electrochemistry of the system permits a much better estimate (6).

Results

Fatigue and Corrosion Fatigue Strengths

In *Figures 1* to *5*, the maximum applied stresses (on a linear scale) are plotted against the cycles to failure (on a logarithmic scale) for each of the five metals investigated, thus providing the basis for what are usually called S/N curves. Table IV lists the plain fatigue and corrosion fatigue strengths at 10^7 cycles observed in the tests. The highest stresses at which the specimens survived 10^7 cycles without breaking were used in this table, provided that no breaks occurred at stress levels lower than this value. Table V lists the ratios between the corrosion fatigue and fatigue strengths at 10^7 cycles for the five metals; i.e., their damage ratios.

For the ASTM 6061-T6 aluminum alloy, the results of the corrosion fatigue tests in Helen mine water were unique in two respects. In contrast with the other two waters, a black tightly-adherent film developed on the wetted strip. Moreover, specimens with completely wetted strips in some instances exhibited breaks on the gauge length which did not intersect the wetted strip. It was assumed, initially, that such specimens should be discarded, but as further data were obtained it became clear that Helen water was insufficiently aggressive to promote corrosion fatigue to any important extent, and that breaks were likely to occur at any point in the gauge length, as in a plain fatigue test. Therefore results obtained on specimens which showed fractures that did not intersect the wetted strips were also tabulated, provided the strip was completely wetted (*Figure 5*). Macrophotographs of typical aluminum alloy specimens, subsequent to corrosion fatigue tests in the three waters, are reproduced in reference (3).

Surface Examination of Fatigued Specimens

Subsequent to the fatigue and corrosion fatigue tests, specimen surfaces were washed gently, to remove loose deposits, and examined using a stereomicroscope with a maximum magnification of 40x. In accordance with general experience (7, 8), specimens

Table III—Analyses of Three Ontario Mine Waters (Levack, Helen, Leitch)

(in parts per million unless otherwise stated)

Source of water		Levack Mine	Helen Mine	Leitch Mine
Reference				
Laboratory number				
Date of sampling				
Storage period (days)				
Temp. at sampling (°C)				
Temp. at testing (°C)		22.8	23.7	24.1
Appearance, odour, etc.				
Organic matter:				
Oxygen consumed ($KMnO_4$)			4	
Chem. oxygen demand (C.O.D.)				
Ultra violet absorption (mu)				
Carbon dioxide (CO_2), calculated			10	4
pH		3.4	7.2	7.6
Colour (Hazen units)		15	0.0	5
Turbidity (Units)		1.5	0.0	10
Alkalinity as $CaCo_3$	(-Phenolphthalein	0.0	0.0	0.0
	(-Total	0.0	83.1	77.7
Susp. matter, dried at 105°C				
" " ignited at 550°C				
Res. on evap., dried at 105°C			1,644	
Loss on ignition at 550°C			353	
Sp. conductance, micromhos at 25°C		3,040	1,897	31,000
Hardness as $CaCO_3$	(Total	1,175	1,079	2,054
	(Non-carbonate	0.0	996	1,977
Calcium	(Ca)	405	245	744
Magnesium	(Mg)	42	113	48
Iron (Fe)	Total	0.46	0.06	1.4
	Dissolved	0.36	0.0	0.11
Aluminum	(Al)	1.4	0.3	0.12
Manganese(Mn)	Total	3.5	0.29	2.0
	Dissolved	3.0	0.00	1.2
Copper	(Cu)	1.58	0.005	0.05
Zinc	(Zn)	0.54	1.7	0.05
Sodium	(Na)	119	25.0	6,870
Potassium	(K)	16.6	8.4	33
Ammonia	(NH_3)	23.8		
		0.56		
Carbonate	(CO_3)	0.0	0.0	0.0
Bicarbonate	(HCO_3)	0.0	101	94.7
Sulphate	(SO_4)	685	830	126
Chloride	(Cl)	629	125	12,078
Fluoride	(F)	0.4	0.18	0.37
Phosphate(PO_4)	Total	0.01	0.0	0.37
	Dissolved			
Nitrate	(NO_3)	0.3	37	19
Silica	(SiO_2)	20	3.1	5.6
Sum of constituents		1,950	1,440	19,921
% Sodium		16	4.8	88
Saturation index at test temperature			0.0	0.0
Stability index at test temperature			7.2	7.6
Sodium Absorption Ratio (SAR)			0.33	

Note: Details of the above terms and procedures are given in the booklet, procurable from the Industrial Waters Section, Mines Branch, 40 Lydia St., Ottawa 4, Ontario, entitled "Industrial Water Resources of Canada, Water Survey Report No. 1, Scope, Procedure and Interpretation of Survey Studies", by J.F.J. Thomas, Report No. 833, Department of Mines and Technical Surveys, Ottawa, Canada (1953).

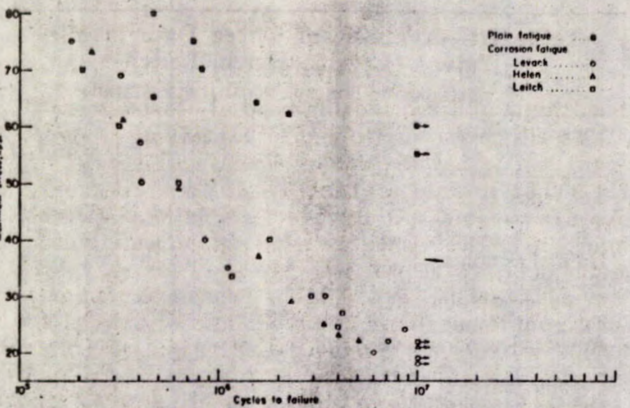

Figure 1.—Fatigue and Corrosion Fatigue Measurements on T-1 Steel.
(United States Steel Corporation).

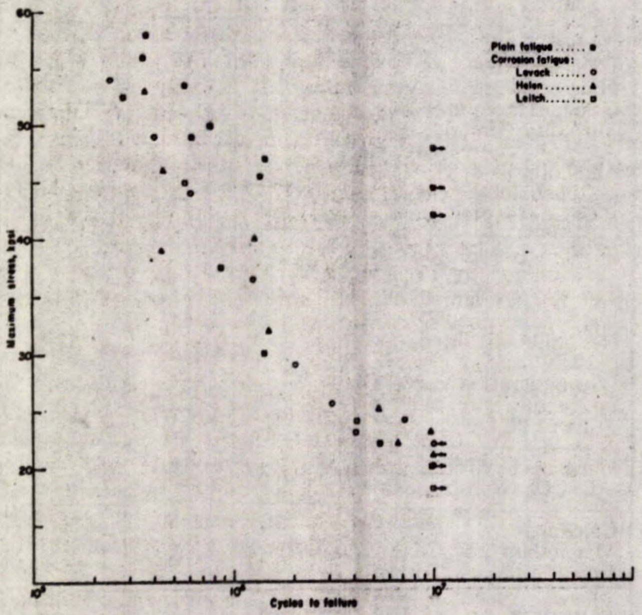

Figure 2.—Fatigue and Corrosion Fatigue Measurements on Abrasive-Resistant Steel.
(The Steel Company of Canada Limited)

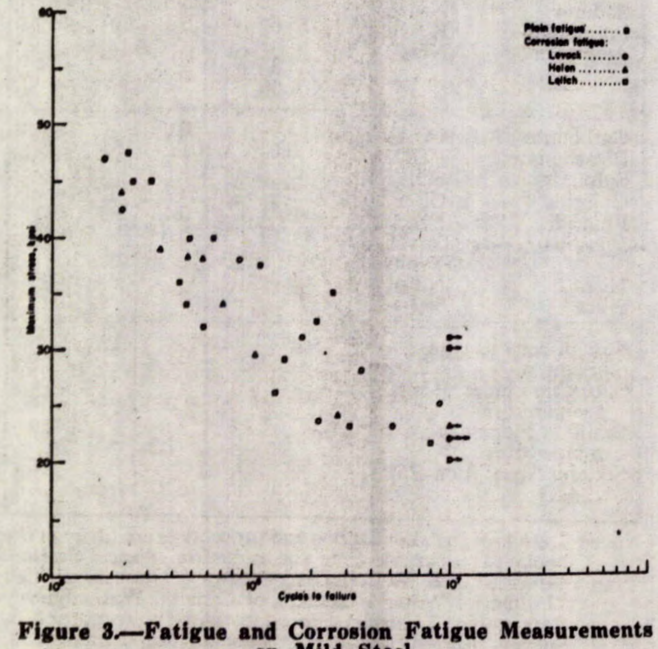

Figure 3.—Fatigue and Corrosion Fatigue Measurements on Mild Steel.
(ASTM Grade A-7)

Table IV—Fatigue and Corrosion Fatigue Strengths at 10^7 Cycles

Metal	Fatigue Strength, psi	Corrosion Fatigue Strength, psi		
		In Levack Water	In Helen Water	In Leitch Water
"T-1" Steel.......	60,000	19,000	21,000	22,000
"Abrasive Resistant" Steel...	44,500	22,000	21,000	18,000
Mild Steel.........	31,000	22,000	23,000	20,000
"Stelcoloy-G" Steel...........	39,000	20,000	16,500	18,000
ASTM 6061-T6 Aluminum......	15,500	10,000	15,500	8,000

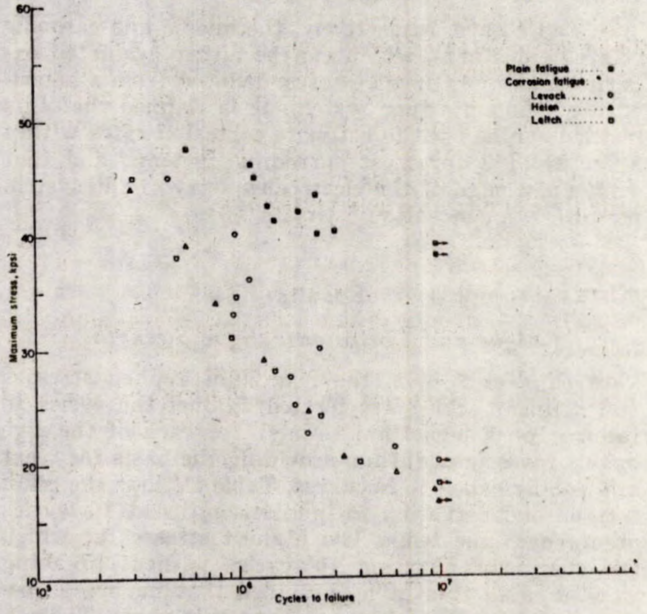

Figure 4.—Fatigue and Corrosion Fatigue Measurements on Stelcoloy G.
(The Steel Company of Canada Limited)

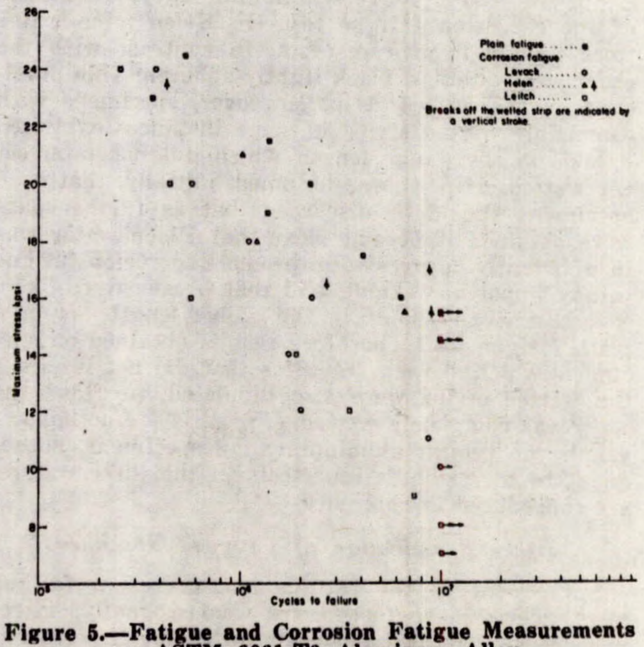

Figure 5.—Fatigue and Corrosion Fatigue Measurements on ASTM 6061-T6 Aluminum Alloy.
(Alcan 65S-T6, Aluminum Company of Canada Limited)

Table V—Comparison between Corrosion Fatigue and Fatigue Strengths

Metal	Damage Ratios (Corrosion Fatigue to Fatigue Strength at 10^7 cycles)		
	In Levack Water	In Helen Water	In Leitch Water
"T-1" Steel	0.32	0.35	0.37
"Abrasive Resistant" Steel	0.49	0.47	0.40
Mild Steel	0.71	0.74	0.65
"Stelcoloy-G" Steel	0.51	0.42	0.46
ASTM 6061-T6 Aluminum	0.65	1.00	0.52

Table VI—Results of 24-hour Corrosion Tests on ASTM Type 6061-T6 Aluminum Alloy in the Mine Waters

Mine Water	Corrosion Rate, mdd*	Macroscopic Surface Appearance
Helen	0, 0, 0	Uniform Corrosion, dark film
Leitch	0, 0, 0	Localized Corrosion
Levack	12, 10, 11.5	Localized Corrosion

*Milligrams/decimetre²/day.
100 mdd = 0.053 inch/year for aluminum alloys.

broken in plain fatigue tests usually showed only a single failure crack. In contrast, specimens which had failed in corrosion fatigue tests usually showed systems of multiple cracks roughly parallel to the main failure.

Examination of the surfaces of the four steels showed that relatively short exposures to Leitch mine water, which has an extremely high chloride content, had produced severe pitting in all cases. A cross section of two typically hemispherical pits is reproduced in reference (3). For the T-1 and Stelcoloy G steels, but not for mild steel and abrasive-resistant steel, the corrosion attack in this water appeared to be more uniform in specimens exposed for longer periods.

In contrast with the Leitch mine water, the Helen and Levack mine waters produced a more uniform and somewhat similar corrosion attack on the four steels. Although small and shallow pits were observed, the severity of pitting attack produced by the Leitch water at its worst was never equalled.

As noted previously, exposure of the 6061-T6 aluminum alloy to Helen mine water produced a dark, smooth, tightly-adherent deposit on the wetted strip, with no apparent loss of metal through corrosion. The other two waters produced a localized attack, the attack being apparently more severe in the Levack than in the Leitch mine water. Metallographic sections showed that the Levack mine water, unlike the Leitch mine water was attacking the aluminum intergranularly (3).

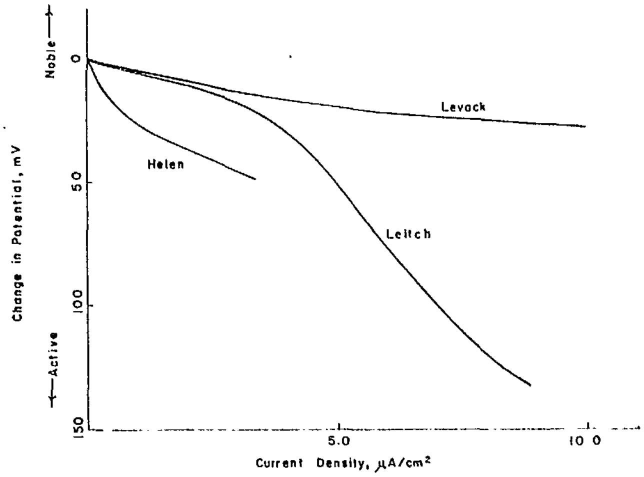

Figure 6.—Model Cathodic Polarization Curves in the Three Mine Waters.

Table VII—Corrosion Rates of ASTM Type 6061-T6 Aluminum after Immersion for 1 hour, Calculated from Polarization Resistances

Mine Water	Specimen No.	Mean Polarization Resistance, R_p, V/A/cm²	I_{corr} Range, µA/cm²	Corrosion Rate Range mdd*
Leitch	1	4,270	6.2 - 12	5.0 - 9.7
	2	4,880	5.4 - 10.5	4.4 - 8.5
Levack	1	3,490	7.6 - 15	6.1 - 12
	2	2,660	10 - 20	8.1 - 16
Helen	1	42,800	0.62 - 1.2	0.50 - 0.98
	2	52,500	0.51 - 0.99	0.41 - 0.80

*mdd = milligrams/decimetre²/day. For aluminum alloys, 100 mdd = 0.053 inch/yr.

Corrosion Tests on ASTM 6061-T6 Aluminum Alloy

Subsequent to the 24-hr corrosion tests, the type of attack caused by the three mine waters was seen to resemble that observed after the corrosion fatigue tests. The results of these tests, including observed weight changes, are summarized in Table VI. It is seen that, in two of the mine waters, average corrosion rates appeared to be too low to be measured by simple weight loss in a test of only 24 hours duration. In the Levack water, which was more corrosive, the measured rate (in terms of a uniform attack) was also low, amounting to approximately 0.005 in./year.

Polarization Measurements

Three model polarization curves, illustrative of the differences in the three mine waters, are reproduced in *Figure 6*. From the repeated polarization scans, a number of values of the average polarization resistance, R_p, were obtained. These appear in Table VII.

In the aerated mine waters used in this work, the cathodic reaction is controlled by the diffusion rate of oxygen, and B_c is therefore equal to infinity. This information is sufficient, according to Stern and Weisert (6), to permit the calculation of corrosion rates to within 40 per cent. Most values of B_a are stated to lie between 0.06 and 0.12. On this basis, the polarization resistance data of the present work yielded the I_{corr} ranges shown in Table VII, with the corresponding corrosion rate ranges shown in the same table.

Discussion of Results

Steels

There appeared to be slight but possibly significant differences in the corrosion fatigue strengths at 10^7 cycles of the four steels, which showed values ranging from a low of 16,500 psi to a high of 23,000 psi (Table IV). Mild steel showed the highest average corrosion fatigue strength of nearly 22,000 psi, and Stelcoloy G steel showed the lowest average value, in the neighbourhood of 18,000 psi. The other two steels showed intermediate and similar average corrosion fatigue strengths. In view of the scatter shown in *Figures 1* to *5*, further measurements would be required to establish the validity of the indicated trends. In agreement with general experience (7, 8), there was no relationship between the average corrosion fatigue strengths and the tensile strengths of the steels.

The corrosion fatigue strengths of the four steels did not show any over-all relationship to water type, and thus no general statement concerning the relative aggressiveness of the three water types on steel was warranted. It appeared, however, that each of the steels showed slight differences in behaviour in the three mine waters. These specific effects could not have been predicted, in most cases. However, it appeared significant that mild steel and abrasive-resistant steel, which showed the greatest susceptibility to pitting corrosion in the high-chloride Leitch mine water, also showed their lowest corrosion fatigue strengths in this water.

Table V presents damage ratios for the metals; i.e., the ratios between corrosion fatigue and plain fatigue strengths at 10^7 cycles. It is seen that mild steel exhibits the highest damage ratios and T-1 steel the lowest of the four steels, with the other two steels showing intermediate values. Damage ratios are seen to decrease with increasing tensile strength and hardness of the steels; i.e., with their increasing susceptibility to fracture.

ASTM 6061-T6 Aluminum Alloy

The corrosion fatigue strengths at 10^7 cycles for 6061-T6 aluminum alloy lay in the range of 8,000-15,500 psi (Table IV). This range was much broader than observed for any of the steels, taken individually, and demonstrated the greater sensitivity of the aluminum alloy to water type. The damage ratios (Table V) also showed considerable variability, ranging from a high of 1.0 to a low of 0.52.

Table VIII—Results in Terms of Strength-Weight Ratios

Metal	Ratio of Fatigue Strength at 10^7 Cycles to Density, 1000 in.	Ratio of Corrosion Fatigue Strength at 10^7 Cycles to Density, 1000 in.		
		In Levack Water	In Helen Water	In Leitch Water
"T-1" Steel........	215	68	75	79
"Abrasive Resistant" Steel....	159	79	75	64.5
Mild Steel.........	107	79	82.5	71.5
"Stelcoloy-G" Steel	140	71.5	59	64.5
ASTM 6061-T6 Aluminum.......	159	103	159	82

The thin black, tightly-adherent film produced by the Helen water was undoubtedly highly protective, as the corrosion fatigue behaviour in this water showed little departure from the plain fatigue behaviour. X-ray diffraction measurements, carried out on portions of the film isolated from the aluminum alloy substrate, failed to show the existence of any crystalline compound. It is therefore assumed that the film was amorphous.

Apparently, the pitting corrosion which occurred in the Leitch water was more damaging than the intergranular attack which occurred in the Levack water, although the latter appeared more severe, from a superficial examination.

The appearance of the specimens after the corrosion tests indicated that waters in which localized corrosion attack occurs (such as Leitch and Levack) bring about pronounced reductions in corrosion fatigue resistance. In Helen water, on the other hand, in which corrosion attack appeared to be much more uniform, resistance to corrosion fatigue was excellent. It appears, therefore, that a qualitative estimate of the corrosion fatigue behaviour of an aluminum alloy might be obtained by a simple immersion corrosion test in a water of interest, followed by an examination to determine the uniformity of the corrosion attack.

The results of the 24-hour weight-loss corrosion tests indicated that the average corrosion rates of the aluminum alloy in Helen and Leitch water were too low to be measured by this method, without resorting to much longer immersion periods, and/or utilizing methods which would remove completely any adherent corrosion product.

The corrosion rates determined from the polarization measurements, on the other hand, were not subject to these limitations. The results of Table VII indicated clearly that Helen water was by far the least corrosive of the three waters, in agreement with its superior corrosion fatigue strength. It must be kept in mind, however, in assessing these results, that the polarization measurements yielded instantaneous corrosion rates applicable to the immersion period of 1-2 hours. Immersion for longer periods would almost certainly have yielded altered corrosion rates. According to some unpublished results obtained in this laboratory, the rates after 16 hours of immersion would have been expected to be lower by a factor of from ⅓ to 1/10 than those of the present report.

General

In considering the results of this research as a whole, the much lower density of aluminum, as compared with iron, must be kept in mind. It is therefore appropriate to make an additional comparison of the five metals in terms of ratios of fatigue strength to density and of corrosion fatigue strength to density, comparable to the tensile-strength-to-density ratios used in rating aerospace materials. The results of this research, in terms of these ratios, are listed in Table VIII, and it is seen that, on this basis, the resistance of ASTM 6061-T6 aluminum alloy to corrosion fatigue appears to be equal to or better than that of the steels in all mine waters.

It bears emphasis that the results of this research apply to the behaviour of bare metals, whereas, in practice, coatings will frequently be employed. It might be noted that if the load-supporting metals in a mine shaft conveyance could be protected from corrosion by impervious coatings kept in excellent condition by careful maintenance, performance could be appropriately assessed by means of the fatigue strengths of Table IV and the fatigue strength to density ratios of Table VIII. The latter table shows T-1 steel to be best and the mild steel worst, with the other three metals occupying an intermediate position.

Conclusions

In providing basic information on the fatigue and corrosion fatigue behaviour of five structural metals used in Canadian mines, the principal objectives of this research have been fulfilled. It should be noted, however, that because conditions will vary widely from one mine to another, and many specific factors not dealt with in this report could be important, considerable care will have to be exercised in drawing general conclusions from the data. It is also evident that the failures of mine shaft conveyances through corrosion fatigue or fatigue of the load-supporting members represent only one of several possible failure modes. In addition, many other factors which are outside the scope of this report must be taken into account when deciding upon the safest and most economical method for extracting ore from a mine.

Cathodic polarization measurements provided a rapid estimate of relative corrosion rates of ASTM Type 6061-T6 aluminum alloy in three mine waters, although the rates were too low to be measured conveniently by conventional weight-loss methods. The results correlated with trends shown by corrosion fatigue measurements in the same waters.

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