

RI 8904

Bureau of Mines Report of Investigations/1984

Corrosion of Friction Rock Stabilizers in Selected Uranium and Copper Mine Waters

By M. M. Tilman, A. F. Jolly III, and L. A. Neumeier



UNITED STATES DEPARTMENT OF THE INTERIOR

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UNITED STATES DEPARTMENT OF THE INTERIOR

William P. Clark, Secretary

BUREAU OF MINES

Robert C. Horton, Director

Library of Congress Cataloging in Publication Data:

Tilman, M. M. (Milton M.)

Corrosion of friction rock stabilizers in selected uranium and copper mine waters.

(Report of investigations / United States Department of the Interior, Bureau of Mines ; 8904)

Bibliography: p. 22-23.

Supt. of Docs. no.: I 28.23:8904.

1. Mine roof bolting. 2. Rock bolts--Corrosion. 3. Mine water. 4. Steel alloys--Corrosion. I. Jolly, A. F. (A. Fletcher). II. Neumeier, L. A. III. Title. IV. Series: Report of investigations (United States. Bureau of Mines) ; 8904.

TN23.U43 [TN289.3] 622s [622'.8] 84-600119

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°F	degree Fahrenheit	lb	pound
ft	foot	$\mu\text{A}/\text{cm}^2$	microampere per square centimeter
g	gram	mpy	mil per year
gal	gal	pct	percent
g/cm^3	gram per cubic centimeter	ppm	part per million
in	inch	psi	pound per square inch
in^2	square inch	yr	year

CORROSION OF FRICTION ROCK STABILIZERS IN SELECTED URANIUM AND COPPER MINE WATERS

By M. M. Tilman,¹ A. F. Jolly III,¹ and L. A. Neumeier²

ABSTRACT

The Bureau of Mines evaluated corrosion resistance of Split Set friction rock stabilizer mine roof bolts to aid in better prediction of useful service life. Electrochemical corrosion testing was conducted utilizing an automated corrosion measurement system. Natural and/or synthetic mine waters from four uranium and two copper mines were the test media for the two types of high-strength, low-alloy (HSLA) steels from which Split Set stabilizers are manufactured, and for galvanized steel. Tests were conducted with waters of minimum and maximum dissolved oxygen content at in-mine water temperatures. Retrieved Split Set stabilizers were also evaluated for property changes.

Galvanized steel was found to be far superior to the unprotected steel in general corrosion resistance; limited tests indicate little tendency to pitting, contrary to behavior for the uncoated steel. Copper-bearing HSLA steel was slightly more corrosion resistant than non-copper-bearing HSLA steel. Statistical analyses resulted in development of equations relating dissolved oxygen, chloride, sulfate, and magnesium contents of mine waters to corrosion rates of the two HSLA steels (nongalvanized). An equation was developed that relates corrosion rates of galvanized steel to mine water temperature and dissolved oxygen content. Variable conditions in mine environments make corrosion damage difficult to predict and emphasize the need for corrosion prevention and control.

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INTRODUCTION

The Split Set³ friction rock stabilizer is a comparatively new type of roof bolt-rockbolt⁴ that has been increasing in use since it was introduced commercially in 1977. Over 20 million Split Set stabilizers have been marketed for use in metal-nonmetal mines. The device is claimed to be particularly useful in rock such as sandstone, soft mudstone, sandy shale, etc. (1-4).⁵ Split Set stabilizers have also been introduced into coal mines on a trial basis during the past several years. The Split Set stabilizer is basically a longitudinally slotted tube with a ring welded on one end (fig. 1) to hold a base plate. In use, the tube is forced into an undersize hole so that compression forces act on the rock over the entire length of the bolt (4-6). This holding action is in contrast to that of the conventional torque-type bolt. The Split Set bolt can continue to hold, sometimes even more strongly, with shifting roof strata where conventional bolts may loosen (2; 7, p. 102). Split Set stabilizers are used extensively in western U.S. uranium and copper mines, as well as other metal mines in the United States and approximately 30 foreign countries. With the development by Ingersoll-Rand of a percussive driver (8) for electrical drilling equipment, the manufacturer expects that Split Set stabilizers will find increased application in coal mines.

This research was conducted under the Bureau's Health and Safety Technology Program to determine detrimental effects of corrosive mine environments on Split Set roof bolts and identify corrosion

³Registered trade mark of Ingersoll-Rand Co.

⁴Although the Split Set friction rock stabilizer is not a bolt in the strict sense that bolts are generally torqued by twisting and/or grouted in place, the term bolt is occasionally used for brevity in discussion.

⁵Underlined numbers in parentheses refer to items in the list of references at the end of this report.

prevention or control methods. The present study deals primarily with six western U.S. uranium and copper mines. The research was expanded to include a gold mine in which Split Set stabilizers are used, when the opportunity arose to study a retrieved Split Set stabilizer from the mine. Research results of the work are intended to aid Mine Safety and Health Administration and mining personnel in better predicting periods during which Split Set installations will remain stable.

Corrosion of metallic roof supports and other items in underground mines is a long-standing and continuing problem.

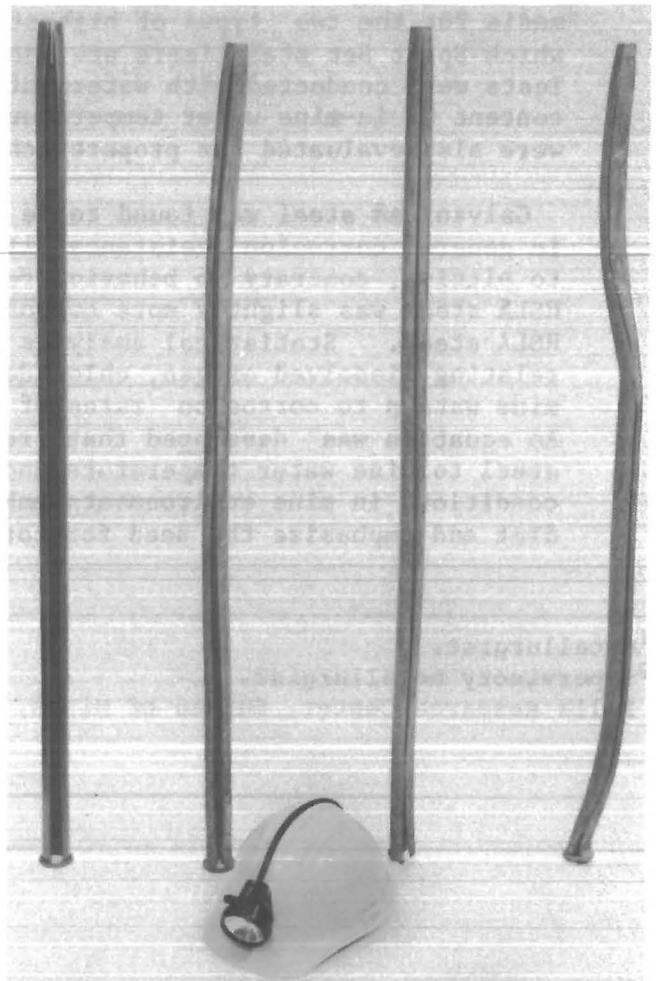


FIGURE 1. - New 4-ft Split Set stabilizer (left) and three Split Set stabilizers retrieved after use in mine roof support.

Relative to traditional type bolts (9), the problem is of particular interest and importance in the case of Split Set stabilizers or other thin-wall roof bolts because of the large surface area and thin wall of the tube. The safety considerations are obvious. The lack of continuous contact between roof bolts and roof strata can also facilitate access of ground water to the bolt surface (5); although this is not unique to thin-wall bolts, the added exposed surface area affords more opportunity for corrosive attack.

Split sets are manufactured and marketed by the Ingersoll-Rand Co. under license from the inventor, James J. Scott. They are fabricated for Ingersoll-Rand by two steel companies from high-strength, low-alloy (HSLA) steels. Bristol Steel Corp. in Pennsylvania uses EX-TEN-H60 and Kaiser Steel Corp. in California uses KAI-WELL-55 steel.

Minimum specified thickness of Split Set stabilizers manufactured from EX-TEN-H60 is 0.086 in. Because of a somewhat lower yield strength, minimum specified thickness of Split Set stabilizers made of KAI-WELL-55 steel is set at 0.090 in.

Split Set stabilizers are formed from strip with average dimensions of 0.092-in thickness and 3.865-in width in standard lengths of 4, 5, and 6 ft with other lengths available.

Calculations indicate the inherent increased susceptibility of Split Set bolts to potential corrosion-related strength degradation, because of their geometry and unique construction. The ratio of the surface area (outer plus inner) to cross-sectional area of a Split Set stabilizer is over three times that of a standard 5/8-in bolt. Comparing a Split Set stabilizer of 60,000-psi yield strength (0.086-in wall) with a 5/8-in diam conventional 60,000-psi bolt, the Split Set stabilizer has a cross-sectional area of approximately 0.356 in² and the conventional bolt 0.307 in². A

uniform 3-mpy corrosion attack on the outer wall of a Split Set stabilizer would annually remove about 0.013 in² of the cross-sectional area, whereas, for the conventional bolt, only 0.006 in² of cross-sectional area would be removed with an attack of 3 mpy because of the smaller surface area. Translated to loss in longitudinal load-bearing capacity, the Split Set stabilizer would lose about 3.4 pct in the yield load, whereas the conventional bolt would lose only about 2 pct. If corrosive attack should occur on the inside of the Split Set stabilizer to the same extent as calculated for the outside, the relative figures would become near 7 pct for the Split Set stabilizer versus 2 pct for the conventional bolt. It should be noted, however, that corrosion has appeared to be predominantly on the outer surface of retrieved Split Set stabilizers. Although these are idealized calculations, the importance of delineating relative corrosive behavior is obvious.

Potential corrosion degradation of installed Split Set stabilizers is particularly difficult to determine. There is no test remotely equivalent to the nondestructive checking of torque of conventional bolts to verify holding power. In the absence of corrosion, such checking is not normally needed because Split Set stabilizers generally will not loosen with shifting of roof strata (2; 7, p. 102). Bureau research (10) has resulted in the development of a device to check for proper Split Set stabilizer installation based on internal volume measurement of the installed Split Set stabilizer. The test equipment, however, cannot evaluate the extent of corrosion degradation. The corrosion problem is further complicated in that some corrosion, within limits, is beneficial in increasing friction between rock and steel (10-11). The use of stainless steel or other highly corrosion-resistant alloys for Split Set stabilizer manufacture would be prohibitively expensive for widespread use; however, galvanized Split Set stabilizers are commercially available.

Although copper, contained in the KAIWELL-55 steel composition, imparts improved atmospheric corrosion resistance (12-13), there is no indication in the literature that copper improves resistance to soil corrosion. With respect to corrosion in water and soils, environment is considerably more important than composition for structural and low-alloy steels (14).

At present, there is no valid method of predicting the service life of Split Set stabilizers. The approach in the present work was to determine corrosion rates with electrochemical tests in representative mine water environments, and correlate loss of metal thickness because of corrosion with reduction in mechanical properties and resultant loss of support capability.

Split Set stabilizers retrieved after a known installation period are a good source of information with respect to corrosion in a particular mine environment. Results of studies of four

retrieved sets are included in this report. Eventually, it can be expected that improved prediction of service life in a given mine environment will be made on the basis of empirical knowledge gained in conjunction with the results of this and related investigations.

At the inception of the project, a literature search was conducted utilizing a computer data base maintained by the Bureau, a literature survey by the National Technical Information Service (15), and various other sources including brochures and literature from the developer and manufacturer of Split Set stabilizers. Over 100 references were identified in the computer search. No references were located regarding specific corrosion studies of roof bolts-rockbolts in mine environments.

The investigation is continuing with the determination of comparative corrosion rates of Split Set stabilizers and galvanized steels in waters from Missouri lead and iron mines.

EXPERIMENTAL PROCEDURE

An electrochemical test method was selected because of the advantage of testing in actual (or synthetic) mine waters in contrast to other accelerated corrosion testing methods that involve exposure of samples to corrosive media substantially more severe than actual conditions. Such accelerated tests are normally pass or fail in nature, and extrapolation to real conditions is difficult at best. The electrochemical method used in the research is most amenable for determining corrosion rates on clean surfaces. Corrosion rates are of questionable validity after the formation of surface corrosion product. The electrochemical method is very useful for comparative purposes such as evaluating different materials or comparing corrosion in different mine waters.

Electrochemical corrosion testing is based on Faraday's law of electrolysis, which relates a quantity of electricity to a quantity of metal in an electrolytic

process. The following equation (16, p. 174), which is an expression of Faraday's law, may be used to determine an instantaneous corrosion rate from the current density:

$$\begin{aligned} \text{Corrosion rate (mpy)} \\ &= \frac{(0.13)(I_{\text{corr}})(\text{E.W.})}{d} \end{aligned} \quad (1)$$

where I_{corr} = corrosion current density, $\mu\text{A}/\text{cm}^2$,

E.W. = equivalent weight of the corroding metal, g,

and d = density of the corroding metal, g/cm^3 .

This equation may be used to calculate the corrosion rate extrapolated to mils per year directly from the corrosion current density. With appropriate operator skill and technical judgment, the

corrosion measurement system (17) used for the research (fig. 2) will determine current densities at related corrosion potentials and calculate corrosion rates.

The corrosion cell, immersed in a controlled-temperature water bath, contained the test solution, specimen, counter electrodes, and standard calomel reference electrode. In operation, the specimen functions as either the anode or cathode as an impressed voltage is varied over a range of positive and/or negative values with respect to the open circuit corrosion potential. Accurate determinations of corrosion rates require tests to determine anodic and cathodic Tafel constants plus a third test, linear polarization, which utilizes the Tafel constants to determine corrosion rates. The microprocessor, housed in the console in

the center of figure 2, after correct programming, automatically plots the voltage versus current density, determines the Tafel constants, and calculates instantaneous corrosion rates projected in mils per year. Selected data are stored on tape for future playback and evaluation.

Test solutions were maintained at the measured in-mine water temperature or at a representative in-mine temperature as suggested by mine personnel. Corrosion tests were conducted in solutions of both minimum and maximum dissolved oxygen contents. Minimum dissolved oxygen contents were achieved and maintained by purging the water with helium (deaeration). Maximum oxygen content (air saturation), which varied with test temperature for given water samples, was maintained by

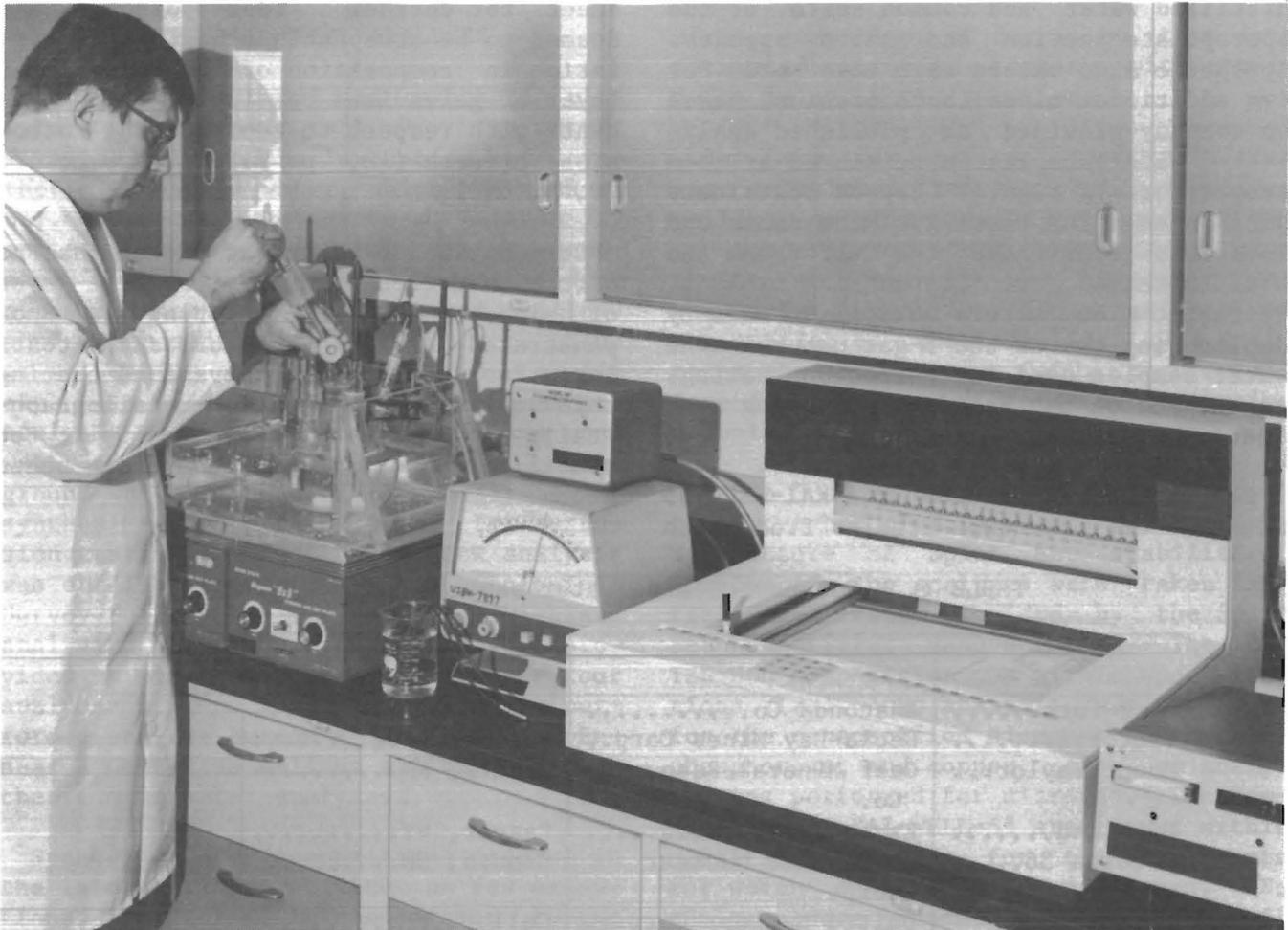


FIGURE 2. - Electrochemical corrosion test equipment, including oxygen analyzer, corrosion cell in constant-temperature bath, resistance compensator, pH meter, and microprocessor with printer.

bubbling air through the test solution (aeration). Oxygen content was stabilized before starting a test. An oxygen meter was used to monitor dissolved oxygen contents.

Water samples were obtained from five western U.S. mines, which included two copper and three uranium mines. Analyses of mine waters were received from a gold mine and an additional uranium mine. Five-gallon samples were obtained from three of the mines, which were sufficient to permit corrosion testing of the two HSLA steels and galvanized steel in actual mine water. The samples were obtained by Bureau or mine company personnel from areas where Split Set stabilizers had been installed. Because only small samples were obtained from two of the mines, synthetic mine water was made (following analysis of the samples) using distilled water and common salts of the appropriate cation and anion species. Synthetic mine waters were also made for two additional mines (both uranium) based on company-provided or published analyses. Water samples were stored at room temperature in tightly capped containers until needed for testing. Mine names and locations from which the water samples were obtained are listed in table 1. Synthetic mine waters were also made by duplicating two of the 5-gal natural mine water samples used in corrosion testing, as a check on the validity of using synthetic solutions.

Samples of EX-TEN-H60 and KAI-WELL-55 steel sheet, the two steels from which

Split Set stabilizers are manufactured, were supplied by the Ingersoll-Rand Co. for use in the corrosion experiments. Scott MTS (Mine Technical Services), Inc., supplied fully formed Split Set stabilizers (fig. 1, left) including galvanized sets (fully formed sets are hot-dip galvanized).

Because the curvature of samples cut from galvanized sets precluded their use in the corrosion test apparatus, which accepts only flat specimens, corrosion tests on galvanized material were conducted on galvanized, plain-carbon steel sheet instead of galvanized Split Set stabilizer steel. (Modification of the specimen holder to permit use of curved specimens proved unsatisfactory; flattening of galvanized set specimens excessively deformed the galvanized coating.) The use of plain-carbon galvanized steel sheet for corrosion test purposes was deemed to be acceptable since slight variation in composition of the outer zinc layer of galvanized coating is insignificant with respect to detrimental corrosion effects (18, p. 712; 19, p. 1157; 20, p. 646).

Composition of the base metal has no effect on corrosion of the surface layer of zinc. The zinc coating was not penetrated during the corrosion testing. For comparison, galvanized coating thicknesses were measured metallographically on samples of galvanized Split Set stabilizers and galvanized flat sheet stock.

TABLE 1. - Sources of mine water samples or analyses

Mine	Company	Location	Principal metal
Carr Fork.....	Anaconda Co.....	Tooele, UT.....	Cu
Victoria.....	Hecla-Day Mines Corp..	Wendover, UT.....	Cu
Mount Taylor...	Gulf Mineral Resources Co.	Grants, NM.....	U
Highland.....	Exxon Co.....	Casper, WY.....	U
Section 36.....	Kerr-McGee Nuclear Corp.	Grants, NM.....	U
Northeast Church Rock.	United Nuclear Corp...	Gallup, NM.....	U
Homestake.....	Homestake Mining Co...	Lead, SD.....	Au

Corrosion test specimens of 0.625-in diam were punched from the steel sheet. Prior to immersion in the test solution, the KAI-WELL-55 and EX-TEN-H60 specimens were ground using 600-grit abrasive paper and were ultrasonically cleaned in ethanol and dried. The galvanized specimens were ultrasonically cleaned but not ground. After insertion in the specimen holder and immersion in the test solution, the specimens were briefly electropolished immediately preceding the test runs. A few test specimens were also machined from a standard 3/4-in roof bolt and subjected to a limited number of tests for comparison with the Split Set stabilizer steels.

Four retrieved Split Set stabilizers were obtained for study. Tensile tests

were conducted on full cross sections of the retrieved sets and metallographic evaluation was conducted on selected samples. Corrosion rates were estimated from the thickness (measured under a microscope) of sound metal remaining in conjunction with the approximate installation periods (metallographic rate determination).

To correlate calculated reductions of tensile and yield strengths with thickness reductions because of corrosion, sheet tensile specimens of EX-TEN-H60 and KAI-WELL-55 steels were ground to nominal 0.075- and 0.050-in thicknesses and tensile tested. Specimens of as-received stock of nominal 0.091- to 0.092-in thickness were also tensile tested to provide baseline values.

RESULTS

WATER AND STEEL ANALYSES

Analyses of natural and synthetic mine waters are shown in table 2. The waters were basic with the exception of synthetic Homestake water, which had a pH of 6.1. Other pH values were between 7.2 and 9.1. The composition of the Homestake synthetic mine water was based on a company-supplied analysis of tailings pond water and did not include a pH value or values for potassium, chloride, or bicarbonate ions. Although the Homestake analysis was incomplete and tailings pond water may not be representative of underground water, the available analysis was synthesized to provide water for corrosion testing. The Church Rock analysis was obtained from a 1977 U.S. Geological Survey publication (21) and the Highland analysis was a commercial analysis provided by mine personnel. The other four analyses of mine water samples were performed at the Bureau's Rolla (MO) Research Center as well as all of the synthetic mine water analyses.

Synthetic water compositions made up in the laboratory were, with a few exceptions, quite close in composition to the natural waters as shown in table 2. The near duplication of natural waters and

close comparison of corrosion test data permitted corrosion testing with confidence in synthetic solutions.

The Langelier (or saturation) indices were calculated from the total dissolved solids, calcium and HCO_3 contents, pH, and temperature, for all natural and synthetic waters except the Homestake Mine sample for which the HCO_3 analysis was not available. The Langelier index indicates the tendency for CaCO_3 to precipitate from water and form a protective deposit.

Table 3 shows chemical compositions of the two types of HSLA steels used for the manufacture of Split Set stabilizers. Samples for the analyses were taken from flat sheet stock provided by the Split Set stabilizer manufacturer. The EX-TEN-H60 composition was within specifications (22). No analysis was performed for the nonspecified elements of sulfur, phosphorous, and copper. Also, no analysis was performed for nitrogen. The composition of KAI-WELL-55 steel was within specifications (23) for those elements for which analyses were performed. No analyses were conducted on KAI-WELL-55 steel for the specified minor elements of sulfur and phosphorous.

TABLE 2. - Analyses of mine waters from western U.S. copper and uranium mines

Mine	Contents, ppm							Total dissolved solids	pH	Langelier index
	Cations			Anions						
	Ca	K	Mg	Na	Cl	HCO ₃	SO ₄			
Carr Fork (Cu):										
Mine sample.....	32	2.8	16	9.6	25	137	28	250	7.9	0.1
Synthetic.....	31	2.5	17	9.5	26	146	30	275	7.2	-.5
Do.....	38	2.2	18	12	31	153	25	233	7.3	-.3
Victoria (Cu):										
Mine sample.....	31	1.9	30	14	18	234	64	492	7.8	.1
Mount Taylor (U):										
Mine sample.....	.8	2.7	.2	238	16	256	313	896	8.4	.5
Synthetic.....	2.9	3.3	.3	260	18	274	328	714	8.2	.2
Highland (U):										
Company analysis	42	7.0	6.9	64	10	195	120	453	7.6	.1
Synthetic.....	38	1.7	20	62	21	198	119	454	7.9	.4
Do.....	16	7.6	14	70	16	144	139	500	7.9	-.1
Kerr-McGee										
Section 36 (U):										
Mine sample.....	70	2.0	17	210	16	198	500	1,023	7.8	.7
Synthetic.....	61	3.0	17	200	22	195	498	880	7.7	.6
Do.....	84	2.9	16	224	23	186	497	900	7.7	.7
Church Rock (U):										
Mine sample ¹	2.1	1.1	0	120	4.8	223	33	312	9.1	.5
Synthetic.....	1.0	1.5	.1	130	8.0	280	38	450	8.9	.1
Do.....	1.6	1.4	.1	59	12	240	37	475	8.8	.2
Homestake (Au):										
Mine sample ²	97	NA	64	110	NA	NA	560	1,115	NA	(³)
Synthetic.....	40	.05	52	77	9.0	15	560	750	6.1	-2.5

NA Not available.

²From tailings pond, company analysis.¹Reference 21.³Not calculated; HCO₃ content not available.

TABLE 3. - Split Set stabilizer steel compositions, weight percent

Element	EX-TEN-H60		KAI-WELL-55	
	Specification ¹	Analysis	Specification ²	Analysis
C.....	Max 0.25	0.23	0.2 - .3	0.3
Cb.....	(³)	.01	NS	NA
Cu.....	NS	NA	Min .20	.32
Mn.....	Max 1.35	1.22	.85-1.30	1.12
N.....	Max .012	NA	NS	NA
P.....	NS	NA	Max .05	NA
S.....	NS	NA	Max .05	NA
Si.....	NS	<.02	Max .12	<.02
V.....	(³)	.01	NS	NA

NA Not analyzed.

²Reference 23.

NS Not specified.

³Specification 0.02 minimum Cb plus V.¹Reference 22, p. 435.

MICROSTRUCTURES

Microstructures of the two steels are shown in figure 3. The EX-TEN-H60 specimen has an essentially ferritic structure with a fine grain size of ASTM No. 13.5. The KAI-WELL-55 specimen has a somewhat coarser grain size of ASTM No. 11 with a pearlite-ferrite microstructure.

An edge view of a galvanized Split Set stabilizer is shown in figure 4. The coating, measured metallographically, is approximately 0.0024 in thick and consists of an outer zinc layer and several underlying zinc-iron intermetallic compound layers.

CORROSION TESTING

Results of corrosion testing are listed in table 4. Corrosion rates obtained in both natural and synthetic waters are shown for EX-TEN-H60 steel in Carr Fork and Mount Taylor waters. Tests were run in both natural and synthetic waters for comparison as a check on the validity of using synthetic waters only as

representative of some mines. Corrosion rates in Homestake synthetic mine water are included for comparison with rates obtained metallographically from a Split Set stabilizer retrieved from the Homestake Mine.

Not listed in table 4 are corrosion rates obtained from testing samples of a standard 3/4-in bolt in Mount Taylor Mine water. At 127° F and O₂ content of 0.1 ppm, a corrosion rate of 2.5 mpy (standard deviation, $\sigma = 1.3$) was obtained for a standard bolt sample in natural Mount Taylor Mine water. Under identical conditions, except for oxygen content, which was raised to the air saturation level of 5.1 ppm, a corrosion rate of 44 mpy ($\sigma = 6.8$) was obtained.

On completion of the total test series, duplicate tests were run in Carr Fork and Victoria natural mine waters and in Church Rock synthetic mine water as a check on reproducibility of data. Good agreement was observed between the two sets of data. The duplicate test data are shown in table 4.

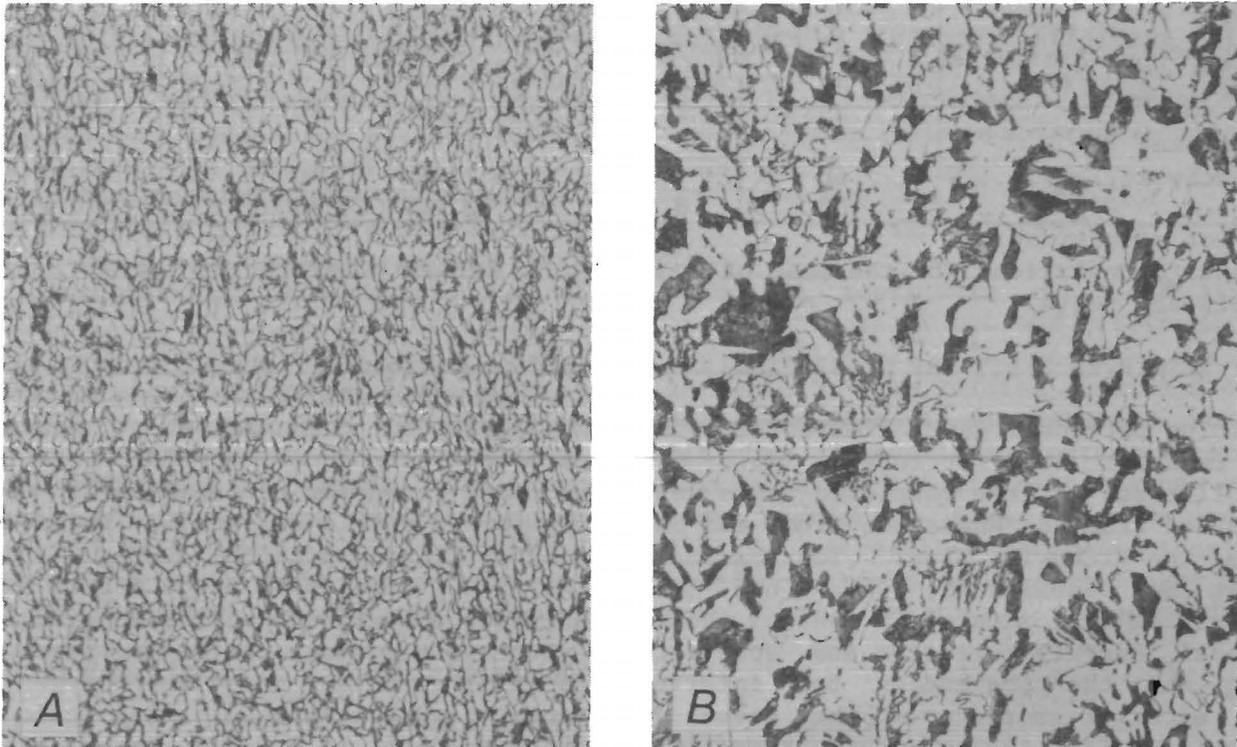


FIGURE 3. - Microstructures (etched, X 500) of high-strength, low-alloy steels used for the fabrication of split set stabilizers. A, EX-TEN-H60; B, KAI-WELL-55.

TABLE 4. - Average corrosion rates of Split Set stabilizer steels and galvanized steel in western U.S. mine waters

(Corrosion rates are for single surfaces)

Source of water or analysis	Test solution temperature, °F	Oxygen content, ppm	Corrosion rate, mpy ¹					
			EX-TEN-H60		KAI-WELL-55		Galvanized	
			Average	σ^1	Average	σ^1	Average	σ^1
Carr Fork:								
Mine.....	68	0.2	1.6	0.3	0.7	0.1	0.3	0.1
	68	8.8	13	.8	11	1.2	2.0	1.1
	68	8.8	² 14	.8	ND	ND	ND	ND
Synthetic.....	68	.2	1.9	.2	ND	ND	ND	ND
	68	8.8	14	.5	ND	ND	ND	ND
Victoria: Mine.....	53	.3	1.0	.1	1.1	.1	.2	.1
	53	10.4	18	2.8	15	3.4	.5	.1
	53	10.4	² 17	2.8	ND	ND	ND	ND
Mount Taylor:								
Mine.....	127	.1	4.2	.6	4.2	.7	.9	.2
	127	5.1	31	3.3	31	2.3	5.4	.3
Synthetic.....	127	.1	6.0	.6	ND	ND	ND	ND
	127	5.1	33	3.1	ND	ND	ND	ND
Highland: Synthetic..	68	.3	2.7	.4	1.1	.4	.4	.2
	68	8.8	45	8.5	30	3.3	.7	.1
Kerr-McGee Section 36:								
Synthetic.....	85	.3	3.2	.6	1.2	.2	1.4	.5
	85	7.4	44	2.9	36	3.7	1.6	.4
Northeast Church Rock:								
Synthetic.....	85	.2	3.7	.3	2.9	.3	.9	.1
	85	7.5	60	3.8	51	5.9	1.5	.3
	85	7.5	² 55	2.2	ND	ND	ND	ND
Homestake:								
Synthetic.....	68	.3	1.6	.5	ND	ND	ND	ND
	68	8.8	17	1.6	ND	ND	ND	ND

ND Not determined.

¹Standard deviations for the mean of four or more linear polarization tests.²Duplicate tests.

RETRIEVED SPLIT SET STABILIZERS

Mining personnel gave limited response to requests for retrieved Split Set stabilizers. Three retrieved sets were obtained from the Homestake Mine and one from the Victoria Mine. The Homestake Split Set stabilizers, which had been in service approximately 9 months, showed general overall corrosion and some pitting near the ring end on both interior and exterior surfaces. The steel is identified from the microstructure (fig. 3A) as EX-TEN-H60. In areas showing

uniform corrosion, metallographic thickness measurements of remaining sound metal permitted calculation of corrosion rates of from 3 to 5 mpy for both interior and exterior surfaces (1.5 to 2.5 mpy for a single surface). These rates compare closely with the average rate on EX-TEN-H60 steel of 1.6 mpy (for a single surface) determined electrochemically in synthetic Homestake tailings pond water containing minimum dissolved oxygen content. Figure 5 shows attached scale in a cross section of a Split Set stabilizer retrieved from the Homestake Mine.

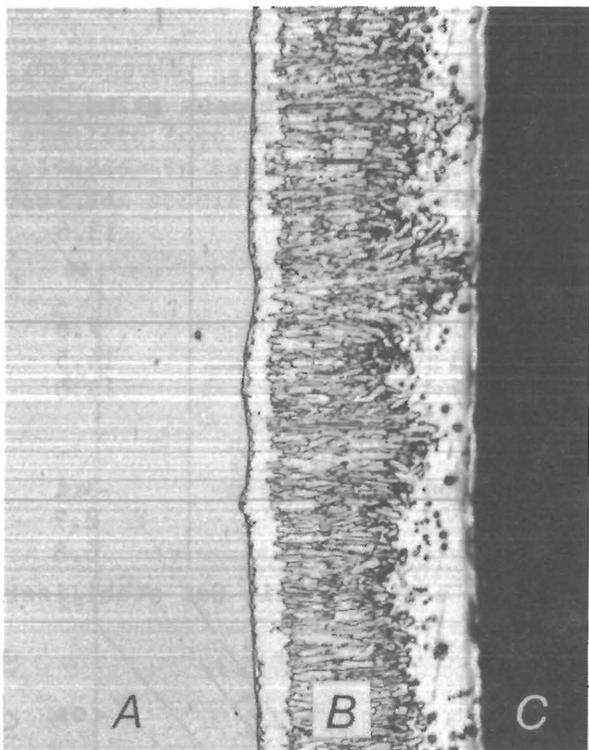


FIGURE 4. - Edge view (X 500) of a galvanized Split Set stabilizer. *A*, Steel (unetched); *B*, layers of zinc-iron and zinc (etched); *C*, specimen mounting material.

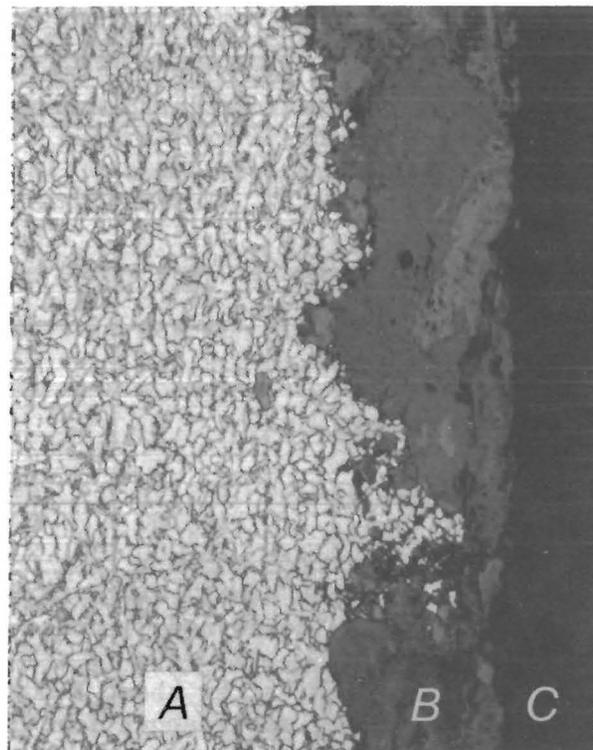


FIGURE 5. - Cross section (etched, X 500) of Split Set stabilizer retrieved after about 9 months in service. *A*, EX-TEN-H60 steel microstructure; *B*, scale; *C*, specimen mounting material.

The retrieved Split Set stabilizer obtained from the Victoria Mine, after approximately 1 yr in service, was somewhat corroded over the entire surface (predominantly over the outer surface). Moderate to severe pitting was also present in some regions--particularly near the ring end. The steel was identified from the microstructure and construction as KAI-WELL-55 (fig. 3B). Corrosion rates for both surfaces determined metallographically ranged from approximately 8 mpy to as high as 68 mpy in a severely pitted region (4 to 34 mpy for a single surface). This may be compared with experimental electrochemical corrosion rates (table 4) of 1.1 and 15 mpy measured for KAI-WELL-55 steel in Victoria Mine water for helium-purged and air-saturated waters, respectively. Pitted areas along the slot appeared to be corroded through,

which would indicate effective pitting corrosion rates of 90 mpy or more in these localized regions. (Average thickness of relatively noncorroded metal was 0.090 in.)

TENSILE TESTS

Tensile tests were conducted on full cross sections of new and retrieved Split Set stabilizers. The results are shown in table 5. The twisted condition of the retrieved Victoria Mine set did not permit use of available extensometers for determination of yield strengths on the test sections. Area calculations for tensile strength determinations were based on thickness measurements of the more sound, relatively uncorroded sections of the retrieved sets.

TABLE 5. - Tensile properties of new and retrieved Split Set stabilizers¹

	Tensile		Yield		Elongation in 10 in, pct
	Load, lb	Strength, ² psi	Load, lb	Strength, ² psi	
New EX-TEN-H60 steel:					
1.....	30,850	84,050	(³)	(³)	14.5
2.....	31,375	85,500	25,600	69,750	11.5
3.....	30,375	82,775	24,050	65,525	13.6
Retrieved ⁴ EX-TEN-H60 steel:					
1.....	30,450	78,875	24,600	63,725	7.6
2.....	32,050	83,025	27,800	72,025	14.5
3.....	32,400	83,950	27,300	70,725	12.0
Retrieved ⁵ KAI-WELL-55 steel:					
1.....	17,300	48,600	(³)	(³)	3.1
2.....	24,200	67,975	(³)	(³)	2.9
3.....	26,050	73,175	(³)	(³)	6.8

¹The 1, 2, 3 for each steel refers to 3 specimens from a given Split Set stabilizer.

²Based on original (noncorroded) cross-sectional area.

³Not obtained.

⁴From Homestake Mine, after about 9 months in service.

⁵From Victoria Mine, after about 1 yr in service.

Calculations of tensile load (maximum before fracture) and yield loads for reduced-thickness Split Set stabilizers are listed in table 6. These are values based on minimum tensile and yield strength specifications for steels used to make Split Set stabilizers. The calculated loads are minimum values that could be expected at corresponding

thicknesses that might result from corrosion. Minimum tensile properties of EX-TEN-H60 are 75,000 psi tensile strength, 60,000 psi yield strength, and 18 pct elongation in 8 in (22). KAI-WELL-55 has minimum tensile properties of 77,000 psi tensile strength, 55,000 psi yield strength, and 23 pct elongation in 8 in (23).

TABLE 6. - Calculated minimum tensile and yield loads¹ of steels used to make Split Set stabilizers, as a function of sheet thickness, pounds

Thickness, in	Tensile	Yield	Thickness, in	Tensile	Yield
EX-TEN-H60			KAI-WELL-55		
² 0.100	28,990	23,190	² 0.100	29,760	21,260
.090	26,090	20,870	.090	26,780	19,130
.080	23,190	18,550	.080	23,810	17,010
.070	20,290	16,230	.070	20,830	14,880
.060	17,390	13,910	.060	17,860	12,750
.050	14,490	11,600	.050	14,880	10,630
.040	11,600	9,280	.040	11,900	8,500
.030	8,700	6,960	.030	8,930	6,380
.020	5,800	4,640	.020	5,950	4,250
.010	2,900	2,320	.010	2,980	2,130

¹Based on cross-sectional area of Split Set stabilizers and minimum tensile strengths of 75,000 and 77,000 psi and minimum yield strengths of 60,000 and 55,000 psi specified for Split Set stabilizers made from EX-TEN-H60 and KAI-WELL-55 steels, respectively.

²Exceeds minimum specified thickness of 0.086 in for EX-TEN-H60 and 0.090 in for KAI-WELL-55 used to make Split Set stabilizers.

Data obtained from tensile testing sheet stock of EX-TEN-H60 and KAI-WELL-55 steels in the as-received condition and after being ground to reduced thickness to simulate loss of material by corrosion are listed in tables 7 and 8. Table 7 gives the specific data for individual

specimens; average data are listed in table 8. Data from tables 6 and 8 are presented graphically in figure 6. Also, included for comparison in figure 6 are data points from a tensile test on a full cross section of a new EX-TEN-H60 Split Set stabilizer.

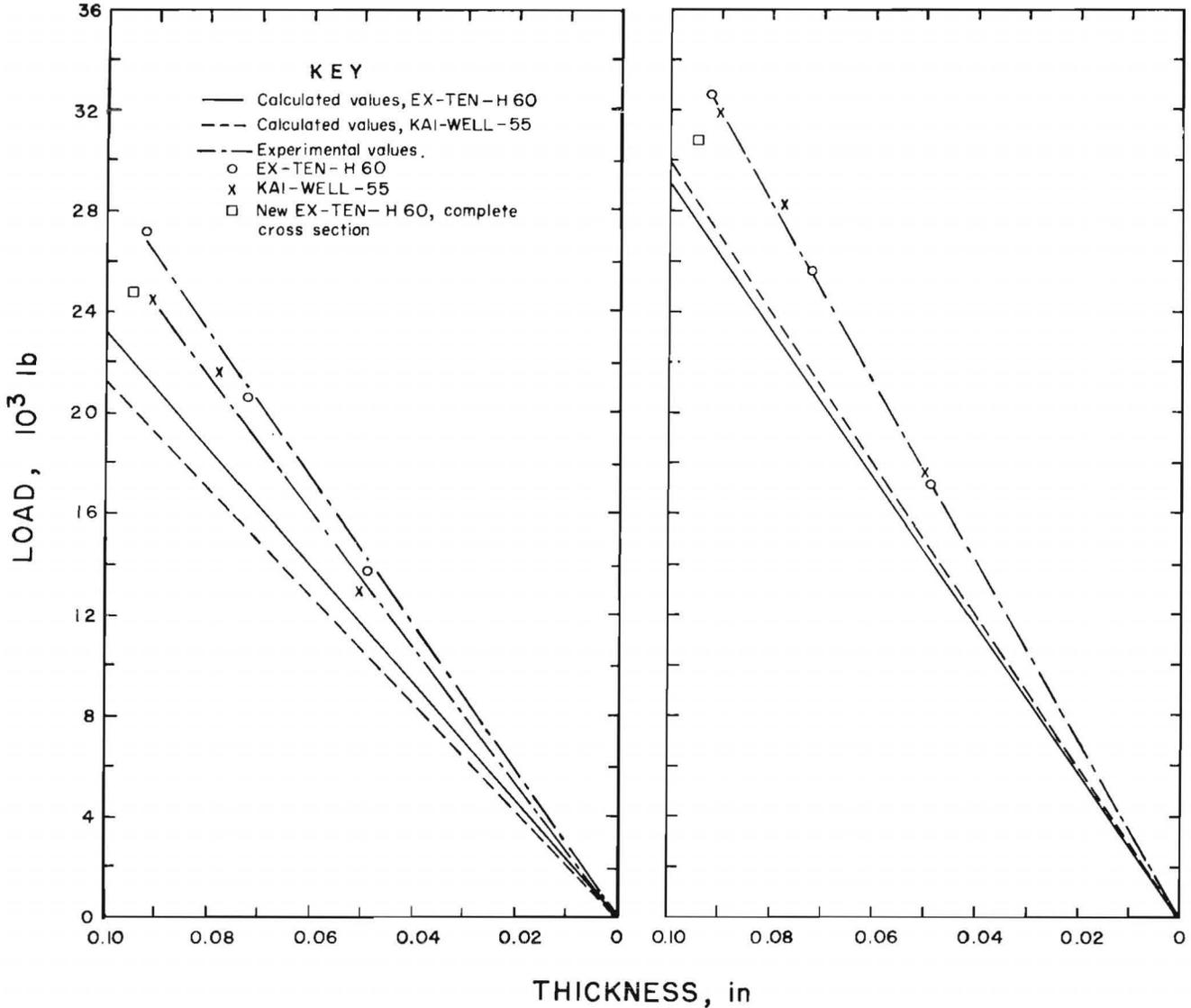


FIGURE 6. - Yield (left) and tensile (right) loads of Split Set stabilizer steels versus wall thickness. Experimental yield loads were determined for nominally 0.25-in-wide specimens and were calculated for the corresponding Split Set stabilizer cross sections of the same reduced thickness. Minimum specified thicknesses are approximately 0.090 and 0.086 in for EX-TEN-H60 and KAI-WELL-55, respectively.

TABLE 7. - Experimental tensile and yield loads of reduced-thickness HSLA steel specimens converted to corresponding values for cross sections of Split Set stabilizer configuration of the same reduced thickness

Specimen thickness, in	Specimen width, in	Cross-sectional area, in ²		Multiplier, stabilizer-to-specimen area ratio	Tensile, load, lb		Yield load, lb	
		Specimen	Stabilizer ¹		Specimen	Stabilizer ²	Specimen	Stabilizer ²
EX-TEN-H60								
0.0490	0.250	0.0123	0.189	15.4	1,100	16,900	870	13,400
.0489	.252	.0123	.189	15.4	1,115	17,200	910	14,000
.0724	.247	.0179	.280	15.6	1,660	25,900	1,340	20,900
.0726	.246	.0179	.280	15.6	1,625	25,400	1,300	20,300
.0923	.256	.0236	.357	15.1	2,175	32,800	1,775	26,800
.0922	.247	.0228	.356	15.6	2,175	33,900	1,875	29,200
.0925	.248	.0229	.358	15.6	2,000	31,200	1,640	25,600
KAI-WELL-55								
0.0492	0.253	0.0124	0.190	15.3	1,060	16,200	800	12,200
.0520	.243	.0126	.201	16.0	1,175	18,800	860	13,800
.0785	.252	.0198	.303	15.3	1,870	28,600	1,500	23,000
.0774	.251	.0194	.299	15.4	1,795	27,600	1,310	20,200
.0908	.247	.0224	.351	15.7	2,025	31,800	1,525	23,900
.0912	.245	.0223	.352	15.8	1,980	31,300	1,440	22,800
.0902	.248	.0224	.349	15.6	2,120	33,100	1,730	27,000

¹Calculated area of Split Set stabilizer configuration of same thickness as test specimen.

²Calculated load derived by multiplying test specimen load by stabilizer-to-specimen area ratio.

TABLE 8. - Average experimental tensile and yield loads of reduced-thickness HSLA steel specimens converted to corresponding values for cross sections of Split Set stabilizer configuration of the same reduced thickness

Specimen thickness, ¹ in	Cross-sectional area, in ²		Multiplier, stabilizer-to-specimen area ratio	Tensile load, lb		Yield load, lb	
	Specimen	Stabilizer ²		Specimen	Stabilizer ³	Specimen	Stabilizer ³
EX-TEN-H60							
0.0490	0.0123	0.189	15.4	1,110	17,100	890	13,700
.0725	.0179	.280	15.6	1,640	25,600	1,320	20,600
.0923	.0231	.357	15.4	2,115	32,600	1,765	27,200
KAI-WELL-55							
0.0505	0.0125	0.195	15.6	1,120	17,500	830	12,900
.0780	.0196	.301	15.4	1,830	28,200	1,405	21,600
.0907	.0224	.350	15.6	2,040	31,800	1,565	24,400

¹Tensile specimens were nominally 0.25 in wide.

²Calculated cross-sectional area of Split Set configuration of same thickness as test specimen.

³Calculated load derived by multiplying average test specimen load by stabilizer-to-specimen area ratio.

DISCUSSION

Although the research was not designed to evaluate specific ion effects, attempts were made to correlate water chemistry and other factors with severity of corrosion of Split Set stabilizer and galvanized steel specimens. Corrosion rates, water composition, test temperatures, pH, and dissolved oxygen content were included in a computerized linear regression analysis. Equations were developed for EX-TEN-H60, KAI-WELL-55, and galvanized steel relating corrosion rates to these variables.⁶ The most useful and meaningful equations relate corrosion rate (mils per year) to dissolved oxygen, chloride, sulfate, and magnesium contents of the mine water for EX-TEN-H60 and KAI-WELL-55 steels. In the case of galvanized steel, dissolved oxygen content and water temperature were found to be the most significant variables.

⁶The authors wish to acknowledge the efforts of J. B. Stephenson, research chemist, of the Bureau's Rolla (MO) Research Center, in performing the computerized linear regression analyses that resulted in the equations development.

The equations developed and corresponding coefficients of correlation, R^2 , were as follows:

EX-TEN-H60 steel

$$\begin{aligned} \ln \text{ corrosion rate} &= 0.303 (\text{O}_2 \text{ conc, ppm}) \\ &- 0.0309 (\text{Cl conc, ppm}) \\ &+ 0.00187 (\text{SO}_4 \text{ conc, ppm}) \\ &- 0.0435 (\text{Mg conc, ppm}) + 1.750, \end{aligned} \quad (3)$$

$$R^2 = 0.96.$$

KAI-WELL-55 steel

$$\begin{aligned} \ln \text{ corrosion rate} &= 0.352 (\text{O}_2 \text{ conc, ppm}) \\ &- 0.0740 (\text{Cl conc, ppm}) \\ &+ 0.00202 (\text{SO}_4 \text{ conc, ppm}) \\ &- 0.0415 (\text{Mg conc, ppm}) + 1.916, \end{aligned} \quad (4)$$

$$R^2 = 0.96.$$

Galvanized steel

\ln corrosion rate = 0.283

(\ln O₂ conc, ppm)

+ 2.557 (\ln temp, °F) - 11.333, (5)

$R^2 = 0.83$.

Sulfate and chloride ions are considered by a number of investigators as the most corrosive of the common ions found in naturally occurring waters, with sulfate generally regarded as the more corrosive (except chloride promotes pitting), while bicarbonate and carbonate ions are considered corrosion inhibitors (12, 24). The presence of magnesium in the equations is probably indicative of interaction between magnesium and one or more anions; magnesium ion itself is not considered as a corrosive constituent.

The coefficient of correlation is an indication of the fit of the experimental data to the predicted curve. A high R^2 indicates good agreement between experimental and predicted values.

Graphs of predicted rates plotted from equations 3 through 5 versus actual rates are shown in figure 7. These plots are a graphic indication of how closely rates predicted from the equations approximate experimental rates. The equations are valid only if water compositions and the other variables are within the limits used to develop the equations, that is, within the maximum and minimum values given in tables 2 and 4.

The ratios of the corrosion rates in air-saturated water to the corresponding rates in deaerated water for the two HSLA steels and galvanized steel in the various mine waters are listed in table 9. Rates in aerated water are up to 30 times higher than rates in the helium-purged, low-oxygen water for the two unprotected HSLA steels. Galvanized steel corrosion rates in aerated water are up to seven times higher than in deaerated water; however, corrosion rates for galvanized steels are comparatively low. The maximum average corrosion rate observed for galvanized steel was 5.4 mpy. This was

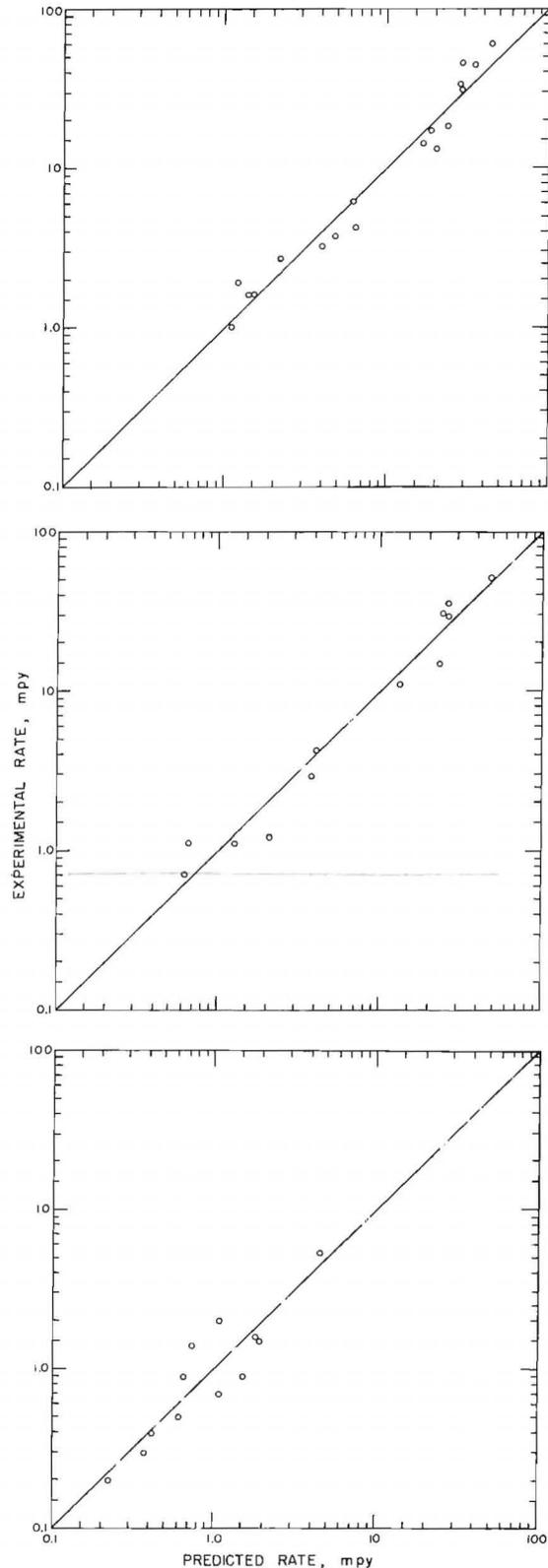


FIGURE 7. - Experimental corrosion rates versus predicted rates for EX-TEN-H60 (top), KAI-WELL-55 (middle), and galvanized (bottom) steels.

TABLE 9. - Ratio of corrosion rate in air-saturated water to corrosion rate in deaerated water¹

Mine	EX-TEN-H60	KAI-WELL-55	Galvanized
Carr Fork.....	8	15	7
Victoria.....	18	14	2
Mount Taylor..	8	7	6
Highland.....	17	27	2
Kerr-McGee....	14	30	1
Church Rock...	16	18	2
Homestake.....	11	ND	ND

ND Not determined.

¹Air saturation by bubbling air; deaeration by helium purging.

obtained in aerated Mount Taylor Mine water at the unusually high temperature of 127° F. Rates on galvanized steel in all other waters were no greater than 2 mpy. Corrosion rates can be expected to normally decrease with time as a result of the buildup of somewhat protective rust layers (13). There are, however, exceptions when the rust product contains certain species such as chloride- or sulfur-bearing constituents that may foster increasing localized attack and accelerated corrosion with time.

The prediction of precise service life of Split Set stabilizers in a specific mine location based on laboratory corrosion tests must be approached with caution (25): "In other words, underground corrosion that has occurred can be explained, but, even today, theory does not permit accurate prediction of the extent of corrosion to be expected to occur and is dangerous unless complete information is available regarding all of the factors present and their individual and inter-related effects...."

Corrosion rates will obviously vary considerably in different mines (and within the same mine) depending on such variables as water and rock (or other roof strata) chemistry, temperature, seasonal variations in water accessibility, ventilation-air flow rates, and humidity. In view of such variable factors, the corrosion rates listed in this report should not be regarded as absolute values but should rather be viewed as a general

and approximate guide for comparative purposes.

Figure 6 (left) shows yield loads as a function of reduced metal thickness based on experimental data and also calculated values from yield strength specifications for the two steels. Figure 6 (right) is a similar plot of tensile loads versus reduced metal thickness. These figures are presented in terms of load (pounds) rather than stress (pounds per square inch) because unit load values are more meaningful from a practical viewpoint than stress in terms of roof support. That is, for a given material, stress values incorporating load to cross section are theoretically unchanged with uniform cross-section reduction, whereas the load capacity reduction is directly proportional to cross-section reduction. Points are included on the figures for a new (unused) Split Set stabilizer. Both tensile and yield loads for the new bolt are above the calculated data on the minimum value curves. The curves based on experimental data extend above the new bolt data, which may be an indication that the flat sheet stock from which the specimens were cut was in a somewhat higher stressed condition than the formed Split Set stabilizer.

Worst case situations can be postulated in which constant loss of metal is occurring with resultant loss of load carrying capacity. As an example, a corrosion rate of 13 mpy was determined for EX-TEN-H60 steel in aerated Carr Fork Mine water. Assuming corrosion on the

exterior (rock contact) surface only, after 1 yr a 0.086-in-thick Split Set stabilizer with a load carrying capacity of about 26,400 lb would be reduced to 0.073-in thickness with a load carrying capacity of approximately 22,425 lb. If the interior surface corrodes at the same rate as the exterior surface, the load carrying capacity would be reduced by twice as much. This type of calculation assumes a uniform rate of corrosion over wide areas; it is realized that this is an idealized behavior not expected to normally be approached in reality.

The Langelier index was calculated for each natural and synthetic mine water used in the investigation and listed in table 2. A positive index of about 0.5 or greater indicates a tendency for CaCO_3 to precipitate a protective deposit (26, p. 502). An index of negative 0.5 or less indicates that CaCO_3 will remain in solution and no protective carbonate deposit can be expected. An increase in water temperature or increase in mineral salt concentration caused by evaporation, will drive the index to a more positive value. Langelier indices for Mount Taylor, Church Rock, and Kerr-McGee Section 36 waters indicate a slight tendency to CaCO_3 precipitation.

Pitting, an insidious and sometimes rapid type of localized corrosion, poses more of a short-term threat of strength loss than does the general overall type of corrosion. Although pitting type corrosion is more often found in metals that owe their corrosion resistance to passivity, pitting can also occur on plain carbon and low-alloy steels (including HSLA) when the corrosion product film is giving protection except at a few isolated spots. Pitting occurs primarily in the presence of halide ions such as chloride and appears to be retarded by the presence of sulfates and other anions. Pitting is believed to involve more acidic solution formation within developing pits.

Prediction of pitting based on laboratory tests is normally difficult and uncertain. A tendency to pitting is more

clearly defined with electrochemical corrosion tests, for metals that readily passivate, such as stainless steel. However, electrochemical corrosion tests can also determine pitting tendency for materials such as low-carbon steels that can passivate in a transient manner under controlled-potential scanning. The hysteresis in forward and backward scanning of voltage versus current density provides an indication of relative pitting tendency of the specimen-solution combination. The corrosion apparatus was programmed to provide pitting-scan test operation.

Pitting scans of a galvanized steel sample indicated a very low tendency to pitting of the galvanized coating. The tests were conducted in Victoria Mine water containing 10.4 ppm dissolved oxygen at 53° F. Moderate to severe pitting had been observed metallographically on a retrieved nongalvanized Split Set stabilizer (KAI-WELL-55 steel) from the Victoria mine. These tests suggest that galvanized Split Set stabilizers may be used to advantage in areas having relatively high chloride ion content. Pitting scans of KAI-WELL-55 steel in the Victoria Mine water confirmed a substantial tendency to pitting under the same conditions that resulted in little or no pitting tendency for the galvanized steel specimen.

It should also be borne in mind that mine roof striations or veins of a corrosive constituent (as chemical constituent and/or relatively high moisture concentration) can lead to localized high corrosion, such as heavy pitting of the Split Set stabilizers where the surface contacts the corrosive constituent. Such corrosive behavior must be assessed on a specific site basis with a knowledge of the mineralization unique to that locality. Nonetheless, with these factors in mind, the collection of general corrosion data in electrochemical tests supported by a knowledge of pitting behavior to the extent possible, can provide important insights as to where particular problems may result and where additional monitoring inspection may be appropriate.

For comparison with Split Set stabilizer steels, corrosion tests were run on samples of a standard 3/4-in-diam roof bolt in Mount Taylor Mine water. The average corrosion rate of 2.5 mpy for the standard bolt in minimum oxygen content water, although somewhat lower than the 4.2 mpy obtained for both Split Set stabilizer steels, can be considered in the same general range. Likewise, the average corrosion rate for the standard bolt steel of 44 mpy in maximum oxygen content water, although higher than the 31-mpy average obtained for both Split Set stabilizer steels, is considered comparable. In general and based on only these few tests, the corrosion behavior (mils-per-year attack) of the standard bolt steel is roughly comparable to the Split Set stabilizer steels in Mount Taylor Mine water, for equivalent area of exposure.

Results of this research and the preceding discussion emphasize the necessity for corrosion prevention or reduction in preference to attempts to precisely predict Split Set stabilizer service life. A workable approach to restricting corrosion is that of galvanizing, which is substantiated by data obtained in the present work. Reference to table 4 shows the much reduced corrosion rates for galvanized samples. Unprotected samples corroded at rates up to >60 times greater than galvanized samples. Galvanized coatings also offer greater pitting resistance.

Figure 4 shows a cross section of a galvanized Split Set stabilizer with an excellent coating. The micrograph shows five zinc-bearing layers totaling 0.0024 in, including the outer layer of unalloyed zinc and four zinc-iron intermetallic compound layers. If the galvanized layer is penetrated during insertion of the set, unless the penetration is gross, the zinc metal (and compounds) will continue to act as a sacrificial anode, corroding preferentially to the steel base until a comparatively large area of steel is exposed, at which time the steel will also begin to corrode. Thus, even if the zinc layer is damaged

on insertion, the Split Set stabilizer will have a significantly longer life than an uncoated set. Galvanized Split Set stabilizers should, however, not be used in areas where ground water has a pH below about 6 or above about 12.5 because, outside of this range, protective films break down and permit rapid corrosion of the zinc itself (27).

Galvanizing increases the initial cost of a 5-ft Split Set stabilizer by approximately 30 pct with no added installation cost. Installing galvanized sets may well be the most economical approach in areas where excessive corrosion is expected. This would include well ventilated wet areas, which provide ample oxygen and moisture necessary for corrosion. Although the research was not designed to reveal effects of specific ions, the deleterious effects of sulfate and chloride ions are well documented (12, 24-25, 28). It would therefore be well to regard areas in which water has high concentrations of these ions as very corrosive and take precautionary measures.

A method of corrosion protection for Split Set stabilizers, as well as conventional steel bolts, that should be investigated further is that of cathodic protection as distinct from general galvanizing. Basically, cathodic protection involves placement in the same environment (mine rock) of a metal or alloy more active (anodic) than the steel to be protected so that the anodic material is consumed rather than the steel. For example, several roof bolts could possibly be connected to a single anode of zinc. Conditions might require impressing an external voltage source on the anode-roof bolt circuit. Or, in the case of thin-wall bolts, a sacrificial zinc anode could possibly be attached directly to each bolt in the manufacturing process.

In some severely corrosive areas, the manufacturer, in cooperation with mine personnel, has installed extra Split Set stabilizers for periodic observation. It is necessary to install short (18 in) Split Set stabilizers, sometimes in over-size holes, if the bolts are to be pulled

for observation of corrosion damage. It should be noted that, under severely corrosive conditions, unprotected Split Set stabilizers are recommended by the manufacturer only for temporary support (29).

An obvious means of corrosion protection would be to manufacture Split Set stabilizers from corrosion-resistant material such as stainless steel. This has been considered but the cost would be prohibitive for general competitive usage. A feasible approach might be to use a more corrosion-resistant, low-to-medium alloy steel with tensile and mechanical properties comparable to present Split Set stabilizers, if a suitable steel is available or could be developed.

Reference to table 4 will show that KAI-WELL-55 steel has slightly lower corrosion rates than EX-TEN-H60 in all waters except the Mount Taylor air-saturated and deaerated waters and the Victoria Mine water of minimum oxygen (deaerated) content. The slightly better corrosion resistance of KAI-WELL-55 is probably because of the copper content, which is known to enhance atmospheric corrosion resistance (12-13), although no reference to improved corrosion resistance of steel in aqueous solution because of copper content has been found.

Because oxygen is required for the occurrence of corrosion (12), a possible means of retarding corrosion is sealing the end of the Split Set stabilizer to prevent air circulation. There have been several reports to the authors, as well as personal observation, of accelerated corrosion occurring on the Split Set stabilizer over a length of about 12 in from the open end. It is thought that the ready access of air and condensate to this area in addition to ground water is the cause of the accelerated local attack.

Roof bolt research at the Bureau's Pittsburgh (PA) Research Center (11), and by Lusignea, Felleman, and Kirby (10), has indicated that pull-out strength of Split Set stabilizers is slightly increased after allowing the bolts to rust somewhat prior to testing. Continued rusting may be expected to increase friction and, consequently, the effectiveness of the bolt; however, at some point, the advantage of increased friction due to corrosion will be offset by the strength loss because of reduced cross section of the bolt.

General corrosion rates determined metallographically on retrieved Split Set stabilizers were comparable with rates determined electrochemically in mine waters of low dissolved oxygen content. Corrosion rates for pitting, when observed, were much higher, as would be expected. In general and based on only a few tests (table 5), it appears that tensile properties hold up very well in areas of Split Set stabilizers where only general corrosion has occurred. Pitted areas, however, result in much reduced tensile properties, particularly elongation, apparently because of the notch effect. As pitting attack progresses, strength will also, of course, become significantly reduced. Evaluation of corrosion effects on retrieved roof bolts of known periods of installation would be of substantial benefit in predicting the extent of roof bolt degradation to be expected in areas where corrosion is a problem.

Split Set stabilizers and other thin-wall roof support devices have a relatively larger surface area exposed to corrosive attack than do conventional roof bolts. At a given corrosion rate, relatively more cross section and strength loss therefore occur for the thin-wall device.

CONCLUSIONS

Because of their large ratio of surface area to cross-sectional area relative to conventional bolts, Split Set bolts are at a disadvantage with respect to corrosion resistance. This must be weighed against the advantage of the unique holding action that permits roof support in soft or shifting strata and has enabled mining of areas where other bolts have been shown to be less effective.

In view of the fact that corrosion rates and corrosion related loss of bolt strength cannot be predicted with certainty, emphasis should be placed on corrosion prevention and control. Galvanizing markedly improves the corrosion resistance of Split Set stabilizer steels in the mine waters examined in this investigation and should be of benefit in mines where ground water pH is between about 6 and 12.5. It should be realized, however, that galvanized coatings are much thinner than the Split Set stabilizer. The galvanized layer can, therefore, still be penetrated with time, even though undergoing corrosion at a much lesser rate than would the unprotected underlying steel. Also, based on limited testing, galvanizing significantly increases resistance to pitting type corrosion, a particularly insidious form of corrosive attack especially difficult to predict. Pitting is localized corrosive action by nature, and, depending on conditions, heavy attack can occur in one region, whereas a nearby region of the steel may be essentially free of corrosion. The electrochemical pitting scan measurements indicate that the HSLA steels used for Split Set stabilizer fabrication are susceptible to pitting corrosion attack.

Results of the investigation indicate that HSLA steel containing copper is slightly more resistant to corrosion from mine water than copper-free HSLA steel. Other low or medium alloy steels of comparable tensile properties should be investigated for corrosion resistance in mine environments.

Another area that should be investigated for roof bolt corrosion protection is that of cathodic protection (sacrificial anodes, as distinct from galvanized coatings). This method is used extensively for protection of pipelines and other underground facilities and may be adaptable for mine roof bolt installations.

Statistical analysis of the data generated in this work indicates that, with respect to corrosion of roof bolts (non-galvanized), the dissolved oxygen, chloride, sulfate, and magnesium contents of mine water provide an empirical indication of corrosiveness. The magnesium ion itself is not considered as a corrosive element but rather the elements or radicals in ionic balance with magnesium, such as chloride and sulfate. Dissolved oxygen is, of course, a primary cause of corrosion. The most important predictive factors with respect to corrosion of galvanized Split Set stabilizers, as revealed by statistical analysis, are water temperature and dissolved oxygen content.

Other research has shown that a limited amount of rust on the outer Split Set stabilizer surface increases friction between rock and metal and improves the effectiveness of the set. Continued corrosion eventually becomes detrimental.

Prediction of corrosion damage to roof bolts can only be done in a limited sense. A number of variables in the mine environment contribute to the difficulty of precise predictions. These variables include water chemistry, dissolved oxygen content and flow rate of water, variations in roof rock strata, temperature, volume and humidity of ventilation air, etc. Despite the number of variables, electrochemical corrosion test data can help predict where corrosion problems may arise with extended installation periods.

REFERENCES

1. Canadian Mining and Metallurgical Bulletin. Split Set Roof Stabilizing System Gives St. Joe Minerals Extra Safety and Economy. V. 64, No. 827, 1981, pp. 188-189.
2. Reed, J. J. Recent Innovations in Rock Reinforcement. Min. Congr. J., v. 65, May 1979, pp. 35-39.
3. Scott, J. J. Continuous Miner and Friction Bolts Play Key Roles in Highlands Move Underground. Eng. and Min. J., v. 178, Dec. 1977, pp. 61-67.
4. _____. Friction Rock Stabilizers--A Different Approach to Ground Support. Min. Eng. (NY), v. 29, July 1977, pp. 59-62.
5. Haas, C. J., R. L. Davis, H. D. Keith, and W. C. Patrick. An Investigation of the Interaction of Rock and Types of Rock Bolts for Selected Loading Conditions (contract H0122110, Univ. MO--Rolla). BuMines OFR 29-79, 1978, 364 pp.; NTIS PB 293 988.
6. Scott, J. J. Interior Rock Reinforcement. Eng. and Min. J., v. 181, Sept. 1980, pp. 79-91.
7. Maher, J. Uniform Four-Foot Length Split Set Roofbolts vs. Uniform Four-Foot Length Fully Grouted Resin Roof Bolts (contract H0242029, White Pine Copper Co.). BuMines OFR 43-78, 1977, 375 pp.; NTIS PB 281 957.
8. Mining Equipment International. Split Set Support Systems Revolutionize Roof Bolting. V. 5, Jan.-Feb. 1981, pp. 45-46.
9. Panek, L. A., and J. A. McCormick. Roof/Rock Bolting. Ch. in SME Mining Engineering Handbook, ed. by A. B. Cummins and I. A. Given. Port City Press, v. 1, 1973, pp. 13-125--13-134.
10. Lusignea, R., J. Felleman, and G. Kirby. Development of a Nondestructive Test Device for Friction Rock Supports (contract H0202030, Foster-Miller, Inc.). BuMines OFR 165-83, 1983, 135 pp.; NTIS PB 83-257519.
11. Bartels, J. (BuMines, Pittsburgh (PA) Research Center). Private communication, June 1981; available upon request from M. M. Tilman, BuMines, Rolla, MO.
12. American Society for Metals. Metals Handbook, Properties and Selection: Irons and Steels. Metals Park, OH, 9th ed., v. 1, 1978, 793 pp.
13. Kamrowski, J. (Results of Investigations on the Corrosion Rate of Low-Alloy Steels in Mines.) Korrosion, v. 2, 1980, pp. 70-75.
14. Larrabee, C. P. Corrosion Resistance of High-Strength Low-Alloy Steels as Influenced by Composition and Environment. Corrosion, v. 9, No. 8, 1966, pp. 259-271.
15. U.S. National Technical Information Service (Dep. Commerce). Anchor Bolts. Citations from the NTIS Data Base, 1970 to April 1980, 66 pp.
16. Ailor, W. H. Handbook on Corrosion Testing and Evaluation. Wiley, 1971, 873 pp.
17. Peterson, W. M., and H. Siegeman. A Microprocessor-Based Corrosion Measurement System. Ch. in Electrochemical Corrosion Testing, STP 727, ed. by F. Mansfield and U. Bertocci. ASTM, 1981, pp. 390-406.
18. American Society for Metals. Metals Handbook. Cleveland, OH, 1948, 1332 pp.

19. American Society for Metals. Metals Handbook, Properties and Selection of Metals. Metals Park, OH, 8th ed., v. 1, 1961, 1300 pp.
20. _____. Metals Handbook, Properties and Selection: Nonferrous Alloys and Pure Metals. Metals Park, OH, 9th ed., v. 2, 1979, 855 pp.
21. Hiss, W. L. Uranium Mine Waste Water--A Potential Source of Ground Water in Northwestern New Mexico. U.S. Geol. Surv. OFR 77-625, 1977, 10 pp.
22. Woldman, N. E., and R. C. Gibbons. Engineering Alloys. Van Nostrand Reinhold, 5th ed., 1973, 1427 pp.
23. Ingersoll-Rand Co. Research staff. Private communication, July 1981; available upon request from M. M. Tilman, BuMines, Rolla, MO.
24. Butler, G., and H. C. K. Ison. Corrosion and Its Prevention in Waters. Reinhold, 1966, 281 pp.
25. Romanoff, M. Underground Corrosion. NBS Circ. 579, April 1957, 227 pp.
26. Uhlig, H. H. The Corrosion Handbook. Wiley, 1948, 1188 pp.
27. Roetheli, B. E., G. L. Cox, and W. B. Littreal. Effect of pH on the Corrosion Products and Corrosion Rate of Zinc in Oxygenated Aqueous Solutions. Metals and Alloys, v. 3, 1932, p. 73.
28. Shreir, L. L. Corrosion. Newnes-Butterworths, v. 1, 1977, 1204 pp.
29. Ingersoll-Rand Co. Questions and Answers About Split Set Rock Stabilizers. 1979, 31 pp.