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Failure Analysis of Diesel Exhaust-Gas Water Scrubbers

**By Robert W. Waytulonis, Sean D. Smith,
and Lito C. Mejia**



UNITED STATES DEPARTMENT OF THE INTERIOR

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FAILURE ANALYSIS OF DIESEL EXHAUST-GAS WATER SCRUBBERS

By Robert W. Waytulonis,¹ Sean D. Smith,² and Lito C. Mejia³

ABSTRACT

The Federal Bureau of Mines contacted 29 organizations--mine maintenance departments and equipment manufacturers--concerning service experience and construction of diesel exhaust-gas water scrubbers. Scrubbers are used primarily on mobile diesel-powered mining equipment subject to 30 CFR 36. Because the scrubbers cool exhaust gas and act as flame arresters, their failure would compromise safety in underground mines.

Scrubber maintenance problems and frequency and modes of failure were identified, and construction materials and techniques were evaluated. Three failed scrubbers were randomly selected from two cooperating mines, and their modes of failure were determined. In conjunction with failure analyses, mine water and scrubber water solution samples were chemically analyzed to characterize corrosive properties.

Sludge and mineral deposits and different types of corrosion and metal fatigue were identified as problems leading to scrubber failure. The corrosion process is explained; maintenance practices, construction materials, and manufacturing methods that could be used to reduce premature failures and allow longer effective scrubber life are identified; and basic changes in scrubber design are suggested.

If type 304 stainless steel is used throughout the scrubber and regular maintenance is performed, long, dependable service can be expected. Other materials such as 304L, 316, or other more exotic steel alloys may be necessary under certain conditions.

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INTRODUCTION

Safe use of diesel-powered mining equipment in underground gassy mines is promoted by the enforcement of certain safety standards to prevent fire and explosion hazards. The U.S. Code of Federal Regulations (CFR) Title 30, Mineral Resources, contains the criteria for certification and approval (permissibility), and some use guidelines for diesel-powered transportation equipment in gassy noncoal mines and tunnels. Equipment used in these types of mines is subject to Parts 36 (18)⁴ and 57 (19). The CFR (30 CFR 57.21-78) specifically requires that only permissible equipment be used in designated parts of gassy underground metal and nonmetal mines. A chapter specifically for diesel equipment in underground coal mines has not yet been established, but the Mine Safety and Health Administration (MSHA) applies Part 36 with some modifications. Thus, diesels in coal mines are also subject to portions of Parts 18 (17) and 75 (20).

At the time of this study there were 1,323 diesel units in all underground gassy mines in the United States. This can be broken down into 621 units in 15 metal-nonmetal mines and 702 units in 75 coal mines. It is not known at what rate diesel use is increasing in underground metal-nonmetal mines but diesel use in underground coal mines has experienced a fivefold increase since 1975. This is part of a trend of increased mine mechanization in the form of diesel-powered load-haul-dumps (LHD's), haulage trucks, utility-service vehicles, and roof bolters. Not all diesel units in underground gassy mines are subject to the mandatory requirement of exhaust-gas conditioning (the use of water scrubbers)

but it is estimated that the majority of the 1,323 units previously mentioned are so equipped.

Reducing the high temperature of the diesel engine exhaust and the hot engine surfaces is necessary for safe operation of equipment in underground mines, particularly gassy mines. The high temperature exhaust gases or hot surfaces such as the exhaust manifold and piping can ignite combustible gases such as methane, and materials such as fuel and hydraulic fluid, or coal dust present in underground mines. Water jacketing of the exhaust manifold and associated piping in conjunction with the engine cooling system will reduce surface temperatures to safe levels.

Historically, devices used to condition diesel exhaust have included (1) spraying water directly into the exhaust-gas stream with subsequent water separation and reuse; (2) directing the exhaust gases through a venturi system that is connected to a reservoir to mix atomized water into the exhaust; and (3) directing the exhaust gases through a water bath with a mist eliminator for entrained water separation and reuse. Each device, however, has its shortcomings; water spray systems are undesirable because the water becomes corrosive and intermixed with fine exhaust particulates. This contamination causes accelerated deterioration and fouls the water pumps and nozzles, and filters require frequent cleaning. The venturi system's effectiveness is mainly affected by metering the correct amount of water to correspond to the exhaust flow rate. Water bath exhaust scrubbers are bulky and require frequent cleaning. Additionally, all of these devices consume large quantities of water.

⁴Underlined numbers in parentheses refer to items in the list of references at the end of this report.

There are two types of water bath scrubbers, the batch-type where all the required water is contained within the scrubber tank, and the water-makeup type where the water level in the scrubber is maintained by a float valve fed from a separate tank. All of the certified equipment in use today use these water bath-type scrubbers. The scrubbers are characterized by high water consumption by virtue of their principle of operation (the operation of a water scrubber as an exhaust-gas cooling device is based on a simple evaporation process). Energy, in the form of heat, from the exhaust gases is used to heat and evaporate the water in the scrubber, thus reducing the heat of the exhaust gas. All of these devices are subject to one or more of the following problems: High water consumption and/or entrained water in the exhaust, excess entrained water in the form of steam affecting visibility, poor reliability of the makeup water float valve, inducing increased back pressure on the engine which degrades performance, and their large size affects vehicle design. Despite these shortcomings, diesel exhaust-gas water scrubbers have proven to be an effective device to cool exhaust gas and act as a flame trap.

Part 36.25(b) requires the system to act as a flame arrester and Part 36.25(c)

requires it to cool the exhaust to a prescribed temperature level. Minimum water levels are usually assured by the float device connected to a reservoir, or in the case of a batch-type scrubber, a low water-level indicator. Scrubbers are designed to maintain enough water throughout a specified period of operation (an 8-hour shift operating at a one-third load factor) to insure against any flame propagation caused from engine backfire or discharge of incandescent particles into a gassy atmosphere and to effectively cool the exhaust during daily operation. If a scrubber should fail to maintain the necessary water level while in operation (through material failure and subsequent loss of water, for example), built-in devices will detect the low water level and shut down the engine in a fail-safe manner. Due to a variety of circumstances it is not uncommon for these devices to be inoperable on mine equipment. Operational failure is defined as the condition of the water-scrubber being such that it will no longer function as it was intended because of a material or component breakdown. However, it is possible that the scrubber could perform the exhaust cooling and flame arresting functions but be weakened (by corrosion for example) to the point that it could not contain an explosion.

ACKNOWLEDGMENTS

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safety engineer, Southern Utah Fuel, Salina, Utah, for contributing the water scrubbers, mine water samples, scrubber solution samples for analysis, and additional insight into the problems reported.

DISCUSSION OF IDENTIFIED PROBLEM AREAS

Sludge and Mineral Deposit Buildup

The most commonly reported scrubber service problems are caused by sludge and mineral deposit buildups around internal baffles and water passages. Particulate matter introduced into the water scrubber

from the exhaust gases and other sources can coagulate to form a heavy sludge. High concentrations of suspended solids in the available water of underground mines is very common. If not removed, these contaminants can restrict the water flow from the makeup tank and

through other internal passages. High concentrations of dissolved solids in the scrubber solution (primarily calcium salts) can lead to mineral deposit build-ups on internal surfaces, which can lead to further plugging.

The severity of both these problems can be reduced if maintenance personnel adhere to rigid scrubber flushing and cleaning schedules. Since the likelihood of this problem increases with the solution residence time, manufacturers usually recommend that water scrubbers be flushed and thoroughly cleaned each day. Household and laundry detergents have been reported to be often used as cleaning agents.

It should be noted that solutions with properties that are harmful to the water scrubber (for example, highly caustic or acidic solutions, solutions containing high concentrations of salt (NaCl), and solutions that will induce electrochemical reactions) should not be used when cleaning and refilling scrubbers. Such solutions can promote accelerated corrosion, which may lead to an untimely failure.

Physical Abuse

The nature of day-to-day operation of equipment underground is generally abusive to diesel exhaust water scrubbers. Mine conditions and scrubber-to-equipment mounting must be considered when designing for long, effective scrubber life. Since scrubbers are usually rigidly mounted to vehicle frames, mine floor conditions can induce stresses that

can cause failure at welds or at mounting points. Dents and holes from inadvertent collisions with surrounding objects have been observed. All such damages must be repaired with welding materials suited to the scrubber material. Figures 1 and 2 show a stainless steel scrubber improperly repaired with welding materials designed for mild carbon steel.

Severe Corrosion of Mild Steel

Three failed scrubbers were obtained at random from two cooperating mines. General corrosion was present in one scrubber that had been in service in a western coal mining operation for several years (fig. 3). Scrubbers 1 and 2 are water makeup type units and are identical in design. The main structure of the scrubbers were fabricated of stainless steel. All internal baffle plates, grates, and supports were of mild carbon steel. While there were no appreciable signs of corrosion on the stainless steel surfaces, severe corrosion appeared on all of the mild steel parts, and at all welds connecting mild steel with stainless steel (figs. 4-5). It can be concluded that corrosion was present because of the following:

1. The mild steel is susceptible to corrosion when exposed to scrubber solution.
2. An electrochemical or a galvanic reaction was induced by the presence of two dissimilar conductors in an electrolyte.
3. A combination of 1 and 2.

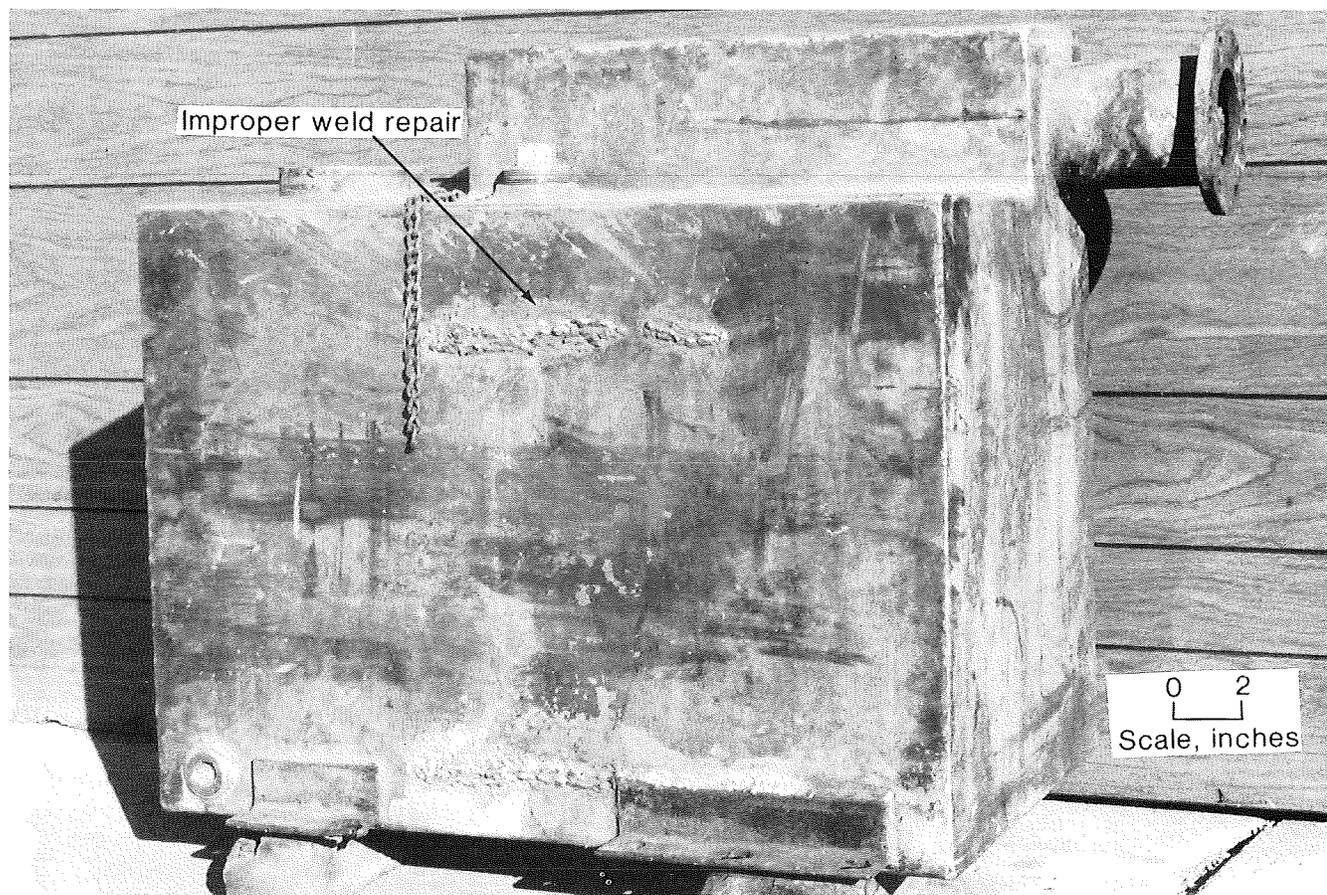


FIGURE 1. - Exhaust water scrubber 3—batch-type—formed of type 304 stainless steel. Arrow indicates improper weld repair where mild steel filler material was used.



FIGURE 2. - Repair site of internal baffle weld failure on scrubber 3.

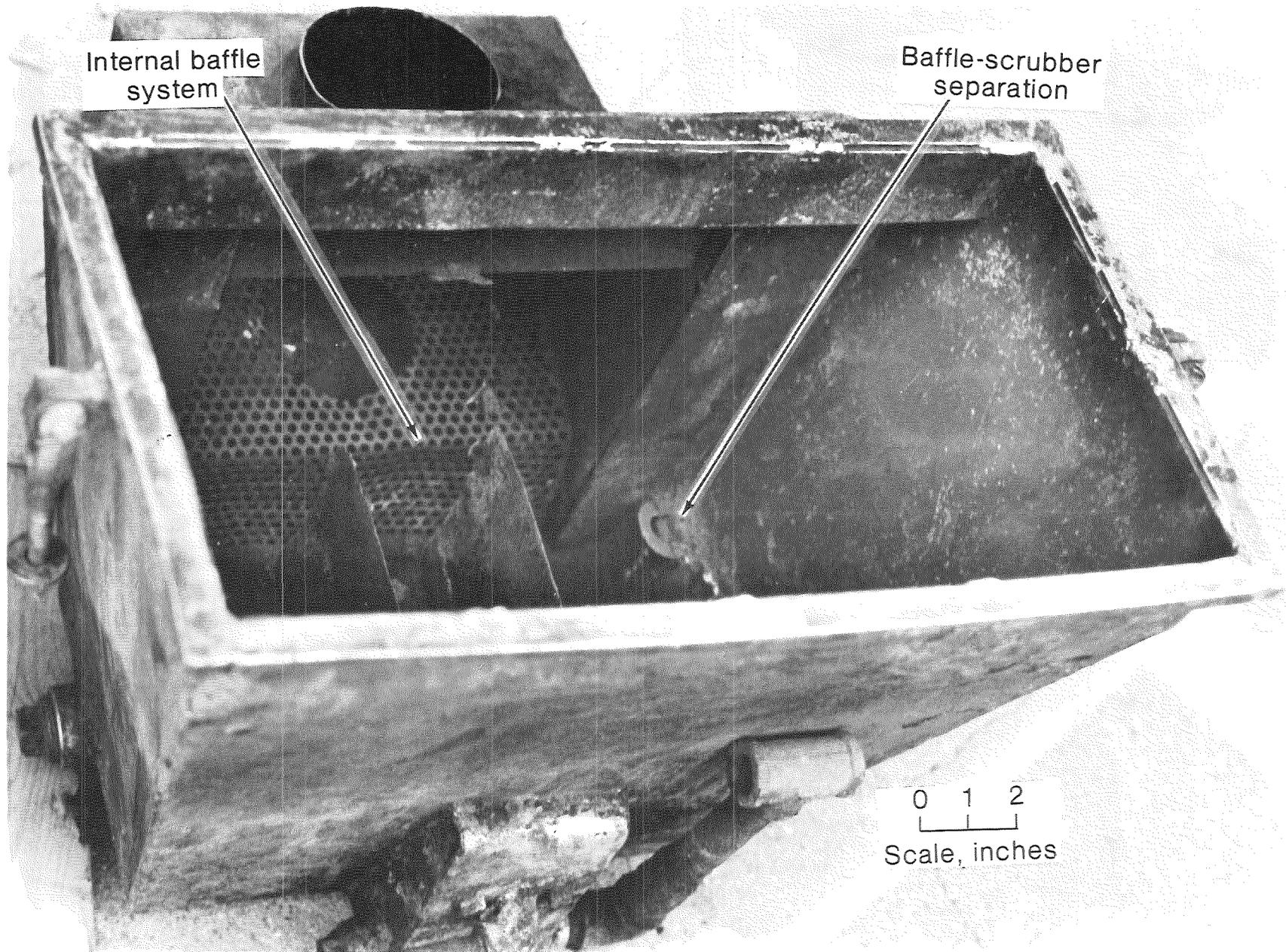


FIGURE 3. - Exhaust water scrubber 1—water-makeup type. Arrows indicate areas represented in figures 4 and 5.

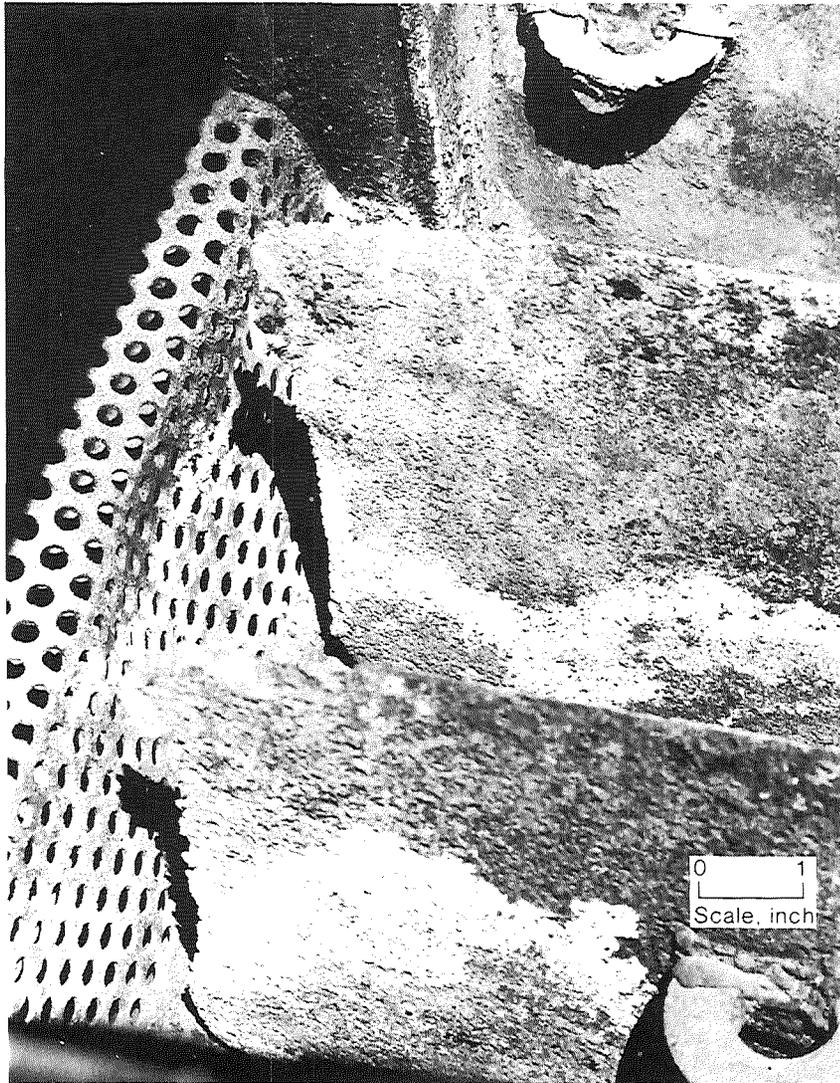


FIGURE 4. - Internal baffle system of exhaust water scrubber. Severe corrosion of mild steel baffles is evident.

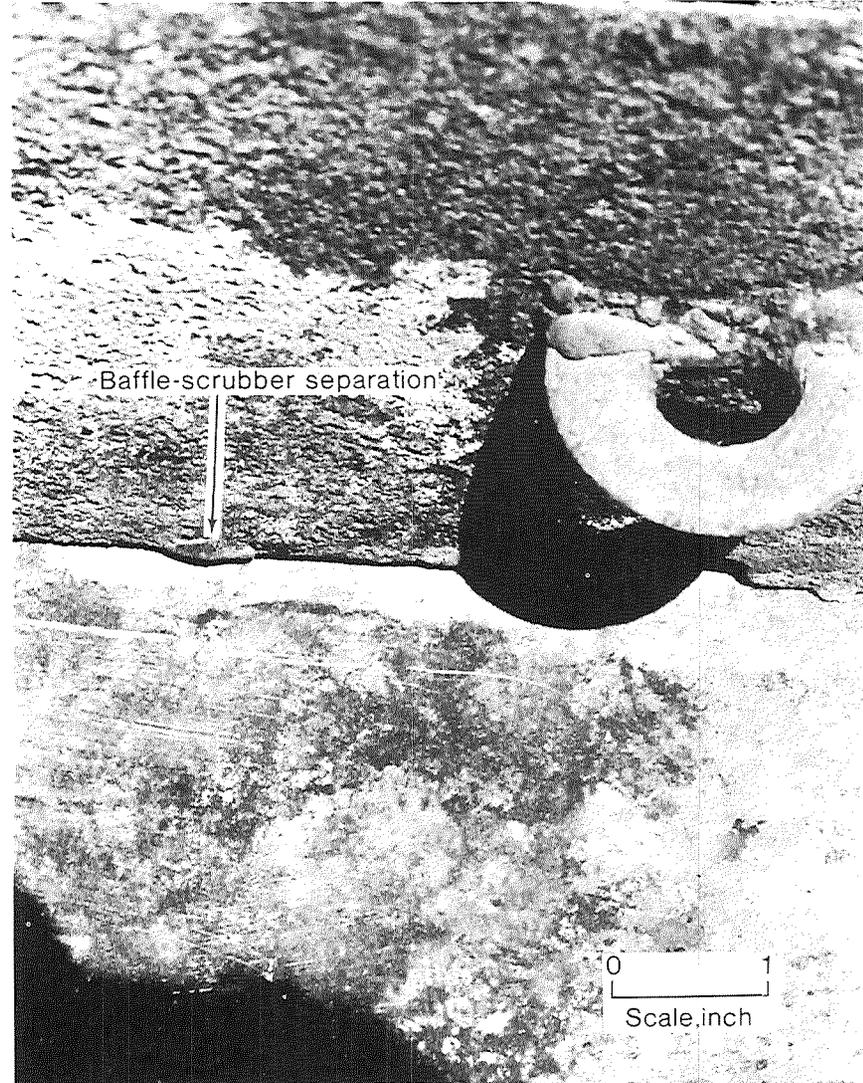


FIGURE 5. - Separation of baffle from scrubber at the weld. This is a typical phenomenon when dissimilar metals are welded.

The corrosiveness of a solution in contact with mild steel depends primarily on the solution temperature, pH, mineral content, and dissolved oxygen content (5). The chemical analysis of the mine water where the failed scrubbers were used indicates that the regional location of the mine plays a determining role in the chemical content of the mine water (tables 1 and 2). Particularly noteworthy are the great differences in the alkalinity and chloride content of the water of an eastern and western coal mine. The problem of pitting corrosion is greatly enhanced by a high concentration of chloride ions. This factor should be considered in the choice of scrubber materials in regions of the United States where mine water is high in chlorides.

Tables 1 and 2 list the chemical composition of mine water before and after a day's shift for several diesel units. It is not known to what extent water was replenished during the operating shift. Solutions containing more than 500 ppm chlorides are at the corrosive threshold for steel and its alloys. The importance of low concentrations of chlorides such as common table salt (NaCl) can be demonstrated by comparing the corrosion problems of scrubber 3 (figs. 1, 2, 6, and 7) with the exhaust tube in figure 8. Scrubber solutions taken from an eastern mine, for example, had filler water low in chlorides. There was no appreciable amount of corrosion of the stainless steel parts of this scrubber. The solution analyzed by Pitt (12) at the University of Utah, however, contained high concentrations of chloride. The raw mine water contained 390 ppm and this level rose to 1,100 ppm after use in the scrubber. It is not known how long it took the chlorides to rise to this level or why this took place. The corrosion present on the tube shown in figure 8 and on the baffle plates shown in figure 4 is characteristic of corrosion due to chlorides (note the high chloride content of mine A water in table 2).

Corrosion is caused by metal exposure to depolarizing agents and is typified by hydrogen evolution. In the presence of dissolved oxygen, when the solution pH is greater than needed for hydrogen evolution ($\text{pH} > 4$), mild steel is usually protected from continuing corrosion by a thin adherent layer of hydrous ferrous oxide film. However, at $\text{pH} < 4$ the protective film can be dissolved and the exposed iron is susceptible to corrosive attack by the electrolyte in the solution. If chloride ions or other depolarizing agents are present, corrosion usually is severe. Mine water often contains ferric sulfate, and is at a low pH, resulting in high corrosion potential (3, 5, 11, 16).

Temperature levels can also be important in a solution's potential corrosion of metals. In an aqueous medium, elevated temperatures will increase corrosive attack of mild steel. Corrosion rate in pure water alone (measured by weight loss) increases twofold for every 30°C (86°F) increase in temperature up to 80°C (176°F) (16). At temperatures greater than 80°C (176°F), corrosion rate decreases to a very low value because at higher temperatures there is decreased solubility of oxygen in water.

Localized corrosive attack in mild steel can also result from the formation of "differential aeration cells." These cells are created when the steel is in contact with an aerated solution at one place, and with an oxygen-deficient solution at another. The oxygen-deficient area acts as the anode of the differential aeration cell and subsequently suffers corrosive attack (14, 16). (Oxygen-deficient areas can be formed in pockets under layers of rust or debris, or within crevices.) Problem areas within scrubbers are most likely to be joints that are not welded on both sides, and other such crevices that might exist from material flaws and fabrication or design oversights.

TABLE 1. - Eastern coal mine water analysis

| | Mine water before use in scrubber | Mine water after 1 shift in scrubber | | | |
|-------------------------------------|---|--------------------------------------|-------|----------|-------|
| | | Scooptram | | Teletram | |
| | | 1 | 2 | 1 | 2 |
| pH..... | 7.1 | 5.55 | 2.44 | 2.33 | 2.8 |
| Acidity ¹ml/l.. | 14.8 | Nap | 42.0 | 102 | 42.0 |
| Alkalinity ²ml/l.. | Nap | 6.9 | Nap | Nap | Nap |
| Composition, ppm: | | | | | |
| Aluminum (Al)..... | <2.0 | <2.0 | <2.0 | <2.0 | <2.0 |
| Calcium (Ca)..... | 0.14 | 0.23 | 0.61 | 0.61 | 0.42 |
| Chloride (Cl)..... | 14.8 | 21.4 | 45.7 | 55.1 | 31.0 |
| Copper (Cu)..... | <0.1 | <0.1 | 0.38 | 0.66 | 1.47 |
| Chromium (Cr)..... | 0.05 | 0.46 | 0.05 | 0.25 | 0.76 |
| Iron (Fe)..... | 0.40 | 1.8 | 12.2 | 20.6 | 7.0 |
| Magnesium (Mg)..... | 48.0 | 65.0 | 203 | 253 | 126 |
| Manganese (Mn)..... | <0.1 | 0.54 | 0.98 | 1.43 | 0.64 |
| Nitrate (NO ₃)..... | 0.94 | 27.5 | 48.5 | 47.0 | 28.5 |
| Phosphate (PO ₄)..... | 0.72 | 0.512 | 0.392 | 5.37 | 0.832 |
| Potassium (K)..... | 17.0 | 33.0 | 67.0 | 90.0 | 47.0 |
| Sodium (Na)..... | 0.062 | 0.11 | 0.26 | 0.32 | 0.16 |
| Sulfate (SO ₄)..... | 460 | 1,180 | 3,800 | 4,680 | 2,270 |
| Zinc (Zn)..... | <0.1 | 30.8 | 1.29 | 5.8 | 61.0 |

Nap Not applicable.

¹Milliliters of 0.204N NaOH used to titrate 1.0 liter of mine water to pH 7.

²As carbonate titrated to pH 4.5.

TABLE 2. - Two Western coal mines water analyses

| | Mine A | | Mine B | | | |
|-------------------------------------|---|--|---|---|--------------|------|
| | Mine water before use in scrubber | Mine water after 1 shift (haulage) | Mine water before use in scrubber | Mine water after 1 shift in scrubber | | |
| | | | | Roof bolter | Haul- age | LHD |
| pH..... | 8.9 | 8.9 | 8.07 | 2.73 | 2.01 | 2.21 |
| Acidity ¹ml/l.. | Nap | Nap | ND | 7.0 | 85.0 | 52.0 |
| Alkalinity ²ml/l.. | 1,700 | 3,300 | Nap | Nap | Nap | Nap |
| Composition, ppm: | | | | | | |
| Aluminum (Al)..... | <2.0 | <2.0 | ND | Nap | Nap | Nap |
| Calcium (Ca)..... | 1.9 | 5.3 | 45.0 | 86.0 | 330 | 120 |
| Chloride (Cl)..... | 1,000 | 720 | 12.8 | 14.2 | 37.7 | 20.8 |
| Copper (Cu)..... | <0.1 | <0.1 | <0.1 | <0.1 | 0.31 | <0.1 |
| Chromium (Cr)..... | <0.5 | <0.5 | Nap | Nap | Nap | Nap |
| Iron (Fe)..... | <0.2 | 0.49 | <0.2 | 2.7 | 32.0 | 2.8 |
| Magnesium (Mg)..... | 0.3 | 1.3 | 33.3 | 40.4 | 132 | 52.0 |
| Manganese (Mn)..... | <0.2 | <0.2 | Nap | Nap | Nap | Nap |
| Nitrate (NO ₃)..... | 0.049 | 89.0 | 0.006 | 3.85 | 26.8 | 29.2 |
| Phosphate (PO ₄)..... | Nap | Nap | 0.008 | 0.102 | 0.99 | 2.99 |
| Potassium (K)..... | 6.9 | 13.7 | 1.2 | 1.7 | 7.9 | 3.2 |
| Sodium (Na)..... | 1.0 | 1.9 | 16.3 | 16.8 | 53.8 | 62.8 |
| Sulfate (SO ₄)..... | <0.05 | 230 | 94.0 | 515 | 2,090 | 696 |
| Zinc (Zn)..... | <0.05 | <0.05 | <0.05 | 0.44 | 1.9 | 1.1 |

Nap Not applicable. ND Not determined.

¹Milliliters of 0.204N NaOH used to titrate 1.0 liter of mine water to pH 7.

²As carbonate titrated to pH 4.5.

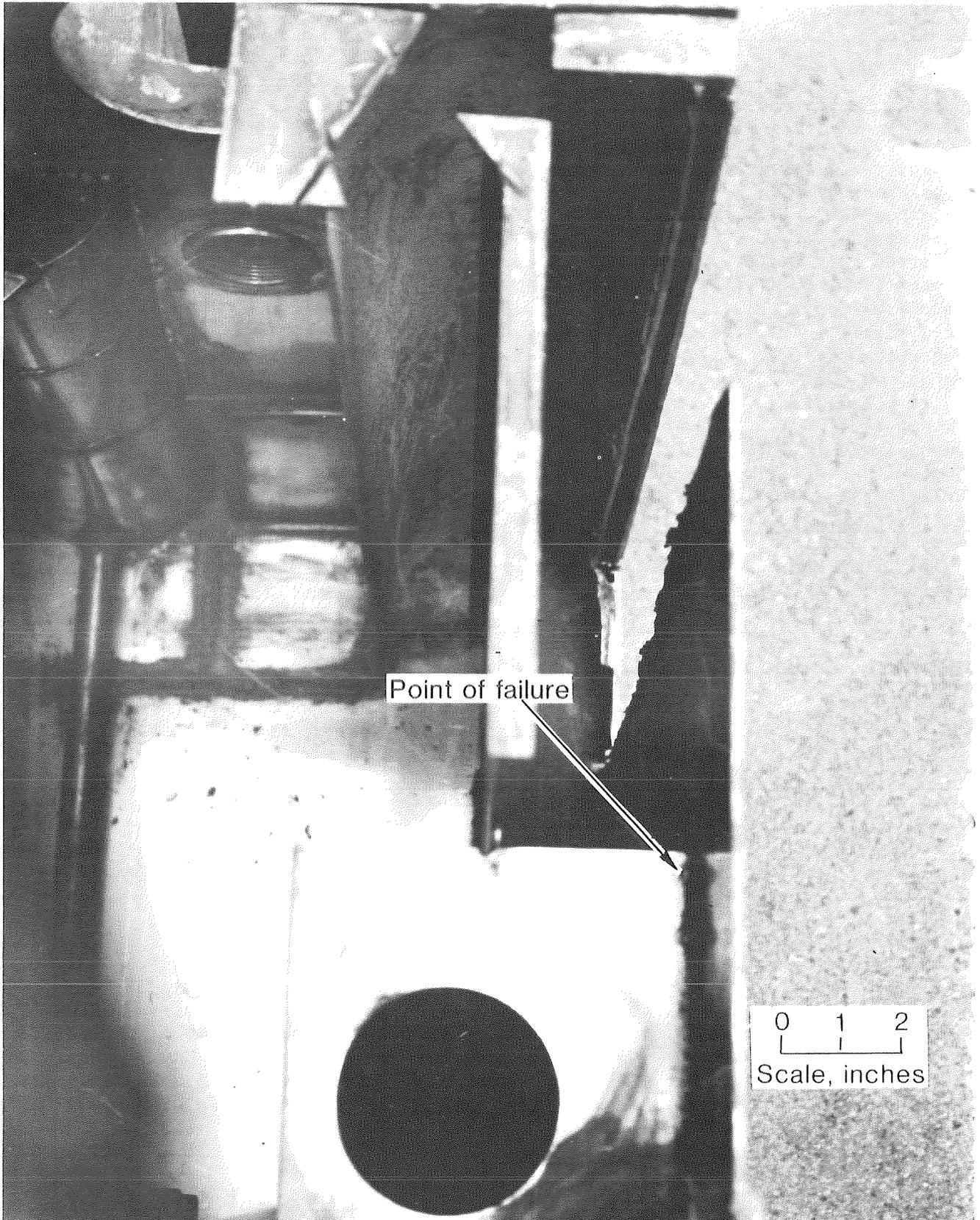


FIGURE 6. - Internal baffle system of scrubber 3. Failure occurred where scrubber and circular baffle were welded.

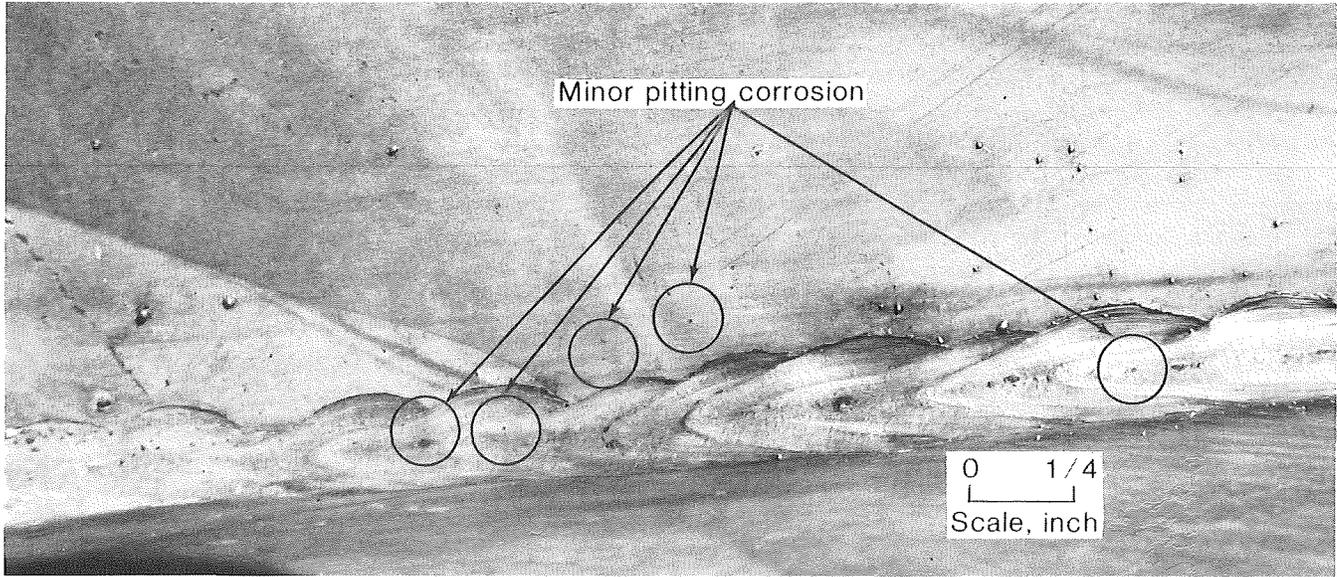


FIGURE 7. - Minor pitting corrosion on and adjacent to welds.



FIGURE 8. - Diesel exhaust tube at water scrubber entry point. Tube shows severe pitting and three-phase corrosion.

Another possible explanation for severe corrosion is that a galvanic cell may be created between the mild and stainless steels. The mild steel serves as the anode as it has a higher electrochemical potential than the cathodic stainless steel. Electrolyte is provided by high concentrations of dissolved minerals, resulting in corrosion of the mild steel.

The corrosion within scrubbers 1 and 2 was most likely a result of the susceptibility of the metal to ordinary corrosive effects, since the scrubber environment appears to be ideal for such corrosion. It would seem that oxygen-rich diesel exhaust gases could introduce sufficient quantities of dissolved oxygen to the solution (1, 6, 13). However, this cannot be verified because chemical analyses of sample solutions were conducted several weeks after the solutions were exposed to the exhaust gases. High concentrations of dissolved solids provided an electrolyte to react with the metal surfaces. With solution pH less than 4, scrubber solution temperatures as high as 65° C (150° F), and chlorine and other known depolarizing agents present, mild steel is subject to corrosion. Molybdenum austenitic stainless steels (316, 316L) are more resistant

to chloride environments and crevice corrosion (3).

The severe decay of many welds between mild steel and stainless steel parts indicates possible galvanic reactions (7). Typically, galvanic corrosion is directly related to the areas of the cathode and the anode. Severe localized corrosion will occur if the anode is much smaller than the cathode. This may be the case where the welds were the anode and the stainless steel walls were the cathode. Accordingly, dissimilar metal welds should not be used for scrubber applications.

Pitting Corrosion of Stainless Steel

Scrubber 3 (fig. 1) was fabricated of type 304 stainless steel and was in service for approximately 6 months in an eastern coal mine. Upon inspection, signs of pitting corrosion on interior surfaces were evident (fig. 7). Since the scrubber was in service for this relatively short time, the pitting corrosion was identified, in addition to that previously improperly repaired. It is believed that the corrosion resistance of stainless steels, as in the case of mild steels, is due to the formation of a thin hydrous oxide film on the metal surface. But, unlike mild steel, this film is further stabilized by the presence of chromium and nickel in 300 series stainless steels. The film is continuous, nonporous, insoluble, and self-healing (that is, under the proper conditions it can regenerate itself if it is destroyed); it "passivates" the metal, reducing its electrochemical potential to about the same low levels as gold, silver, platinum, and other noble metals (4-5).

Without the passivating protection of the hydrous oxide film, the electrochemical potential of the metal approximates that of ordinary iron. As a result of the breakdown of passivity, pits are created at susceptible nuclei on the metal surface. Disruption of passivity can result from inhomogeneity of the metal surface, deposits on the surface, or complete breaks in the hydrous oxide

film. Once a pit is started, an electrolytic cell is formed. The "active" area of the pit (which has the electrochemical potential of iron) is the anode, and the much larger area of the unaffected passivated region (electrochemical potential of the noble metals) is the cathode. The large chemical potential difference between the anode and the cathode, in the presence of depolarizers (that is, dissolved oxygen and oxidizing salts) induces a strong corrosive action. Since corrosion is related to the ratio of anode area and cathode area, as well as to the effects of the environment (temperature, agitation, maintenance), the size, frequency of occurrence, and depth of pitting varies.

Suspended matter introduced into the solution from exhaust gases can act as an abrasive and prevent the formation of the passivating film. Mineral deposits and sludge adhering to interior metal surfaces could also reduce the corrosion resistance of the material. Although scrubber solutions can contain sulfate and nitrate ions that help to further passivate stainless steels (8, 21), the extraordinary conditions mentioned can overcome the passivity. When temperatures greater than 65° C (150° F) and sufficient concentrations of depolarizers are present in solution, rapid penetration of the metal may occur. Depolarizers are introduced by replenishment water, by the exhaust gases, or are redissolved into solution from mineral deposits on the interior surfaces.

Once a pit and its electrolytic cell is formed, it becomes more difficult to restore passivity to the damaged area. In order for stainless steel to remain passive, oxygenating agents must be replenished constantly to maintain the hydrous oxide film.

Since the base of a pit is less accessible to these agents, the metal is unlikely to regain its passivity. Pitting corrosion tends to penetrate the parent metal. The area surrounding the pit remains passive, and the surface area within the pit remains active. With this

tendency to penetrate, rather than to spread along the surface, corrosion at one pit can advance through the entire thickness of the parent metal. Corrosion perforating a metal wall would result in operational failure of the scrubber. To prevent such failures, scrubbers must be periodically inspected for pitting corrosion if internal surfaces are accessible. Isolated pits should be repaired by proper stainless steel welding practices. Repair welding of corrosion pits in stainless steel can cause sensitization that can lead to still more corrosion. Rapid quenching of the weld area (heat-affected zone) will reduce carbide formation and sensitization. Additionally, if stainless steel is welded on one side and the opposite side is not protected from the atmosphere, it will become oxidized and lose its inherent passivity (7).

In the presence of a chloride-rich solution, a three-phase corrosion (15) of the exhaust tube shown in figure 8 occurred at the water level. There, agitation, high temperature, and the dissolved depolarizing agent plus oxygen in the exhaust stream contribute to the breakdown of the stainless steel. The mine water tested was characteristically basic (high pH) and contained about 1,000 ppm of chloride (table 2). At temperatures greater than 65° C (150° F) the high concentration of chloride ions provide the probable cause of the pitting that is observed near the welds and at the water level of the exhaust tube (2, 15). (See figs. 7 and 8.)

Also, the sensitization of stainless steels by the intense heat generated during welding fabrication further promotes corrosion, particularly on the internal surfaces adjacent to the welds. During the welding process, an area adjacent to the weld undergoes intergranular carbide precipitation. Except for the extra-low-carbon grades of type 300 series stainless steels, or those containing a stabilizing element such as titanium, particles of chromium-containing carbides precipitate at grain boundaries during sensitization which lowers the corrosion resistance at the grain boundaries

(7, 10). The corrosion resistance of stainless steels is due to the presence of chromium in the material. The localized nature of corrosion near the welds indicates reduced resistance from intergranular carbide precipitation (fig. 9). Although the range varies with time and alloy content, sensitization occurs between 650° and 870° C (1,200° and 1,600° F) (16). The decreased corrosion resistance is attributed to the presence of chromium-rich carbides at the grain boundaries and the depletion of chromium in the adjacent matrix (9). Extra-low-carbon stainless steels (304L, 316L) have increased immunity to this problem, but are not without their problems. When welding extra-low-carbon steels, care must be taken to use the proper weld filler (extra-low-carbon welding rods), and surfaces to be welded must be cleaned of grease, oil, and other carboniferous materials. Use of general purpose welding rods is not recommended. When possible, all joints should be welded internally and externally to guarantee adequate penetration. The weld area must

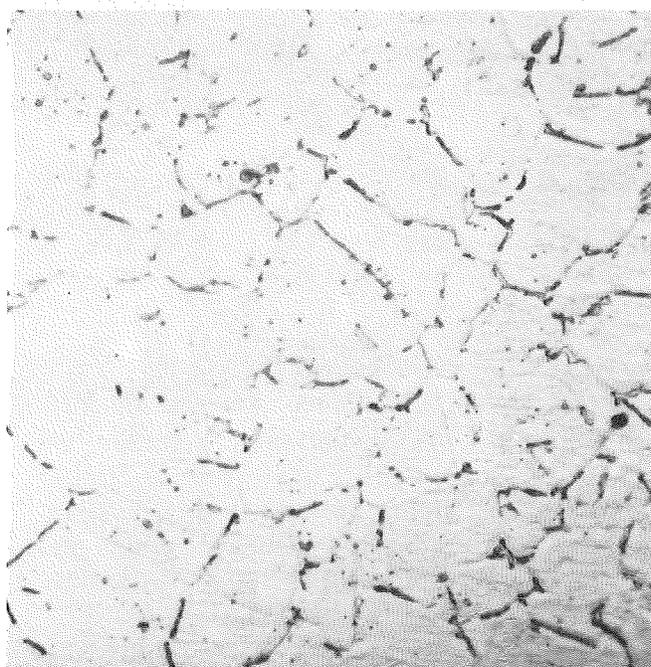


FIGURE 9. - Carbide precipitation at grain boundaries. Precipitation is generated by the high heat of welding (sensitization) which enhances pitting corrosion (X 100).

be properly cleaned to obtain a sound weld. It is noted that many mines do not have the equipment, material, or expertise to weld stainless steel.

Fatigue Cracks at Welds

A section of a typical corner weld from stainless steel scrubber 3 was removed and the microstructure is shown in figure 10. The grain structure in the upper half of the photograph is the parent material, while the lower half shows the weld metal with typical dendritic structure. The discontinuity in between is the result of inadequate weld fusion. As a result, a fatigue crack initiated from this discontinuity and propagated from the inside root of the weld. While

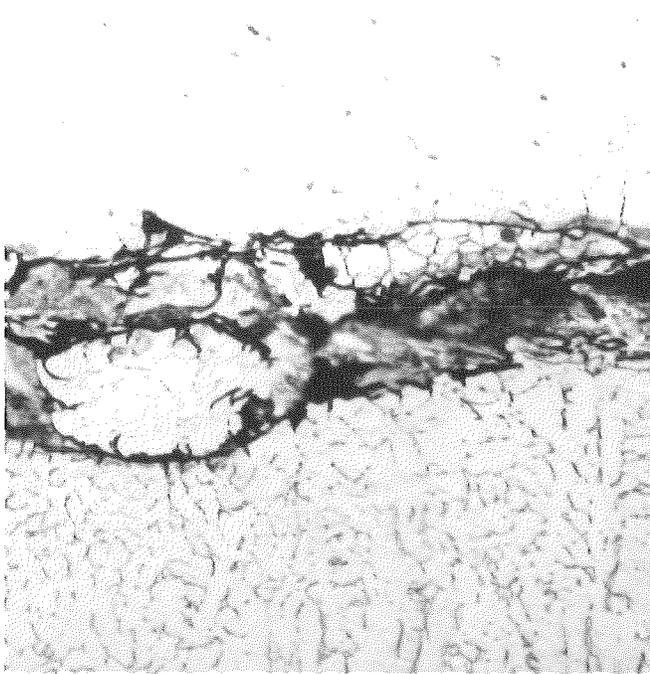


FIGURE 10. - Inadequate weld penetration in a typical corner weld. Smaller grains are the welding material (note the presence of carbide precipitation) (X 100).

other factors led this scrubber to fail, this fatigue crack may have led to eventual failure as well. Cracked corner welds was a problem often heard in conversations with mine maintenance personnel. To eliminate this problem, it may be necessary to weld these joints on both sides of the corner.

The cracks in figures 11, 12, and 13 occurred near welds which joined the circulatory section of a stainless steel scrubber to the scrubber wall. The cracks resulted from fatigue stresses concentrated at intermittent welds and occurred entirely within the base metal of the wall, adjacent to the weld. Beginning at the inside surface of the scrubber, the cracks then propagated through the metal thickness until the remaining cross section was insufficient to support the applied stresses. The ratchet marks on the crack surface (fig. 12) are characteristic of high stress and originate from numerous fatigue cracks. Several small fatigue cracks combined to form the single crack which eventually led to failure.

The applied stresses were likely caused by equipment vibration and exhaust pulses acting on the baffle section of the walls. The lack of rigidity along the entire weld joint allowed the sections to vibrate and resulted in fatigue cracks. It is suggested that by replacing intermittent welds with a continuous weld, the system's vibration could be reduced. In figure 13, a crack is shown to have formed at the sharp 90° angle in the baffle plate. It is not advisable to use such abrupt cuts, since stress will concentrate there and the amount of load required for crack propagation is greatly reduced. Accordingly, such cuts should be rounded.

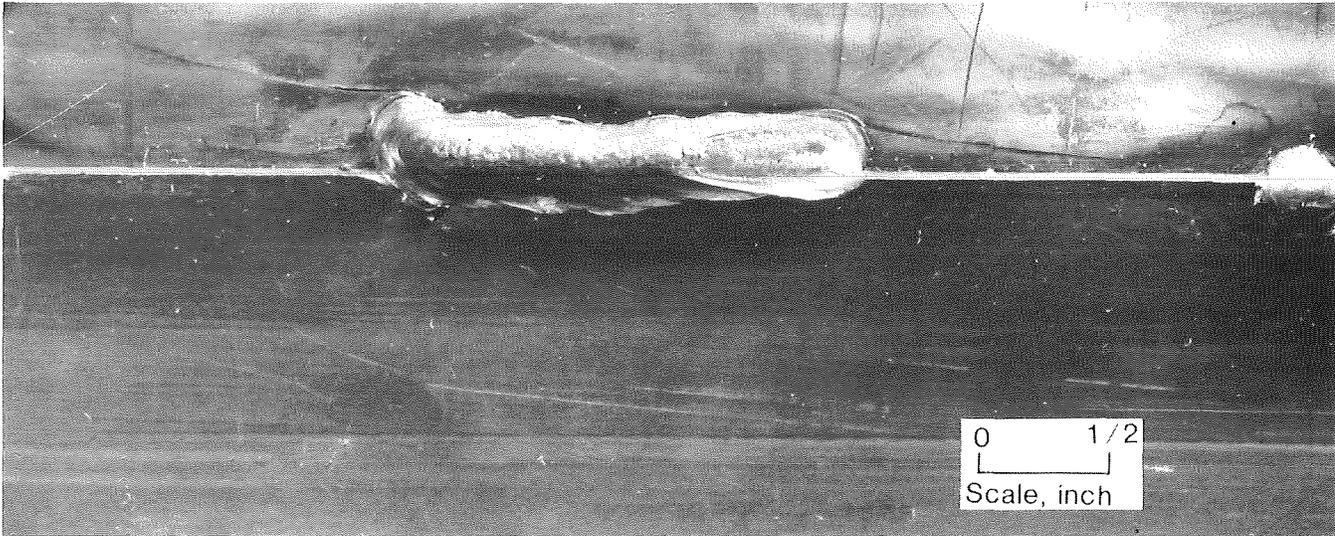


FIGURE 11. - Fatigue crack at an intermittent weld. This is the externally repaired crack shown in figure 1.

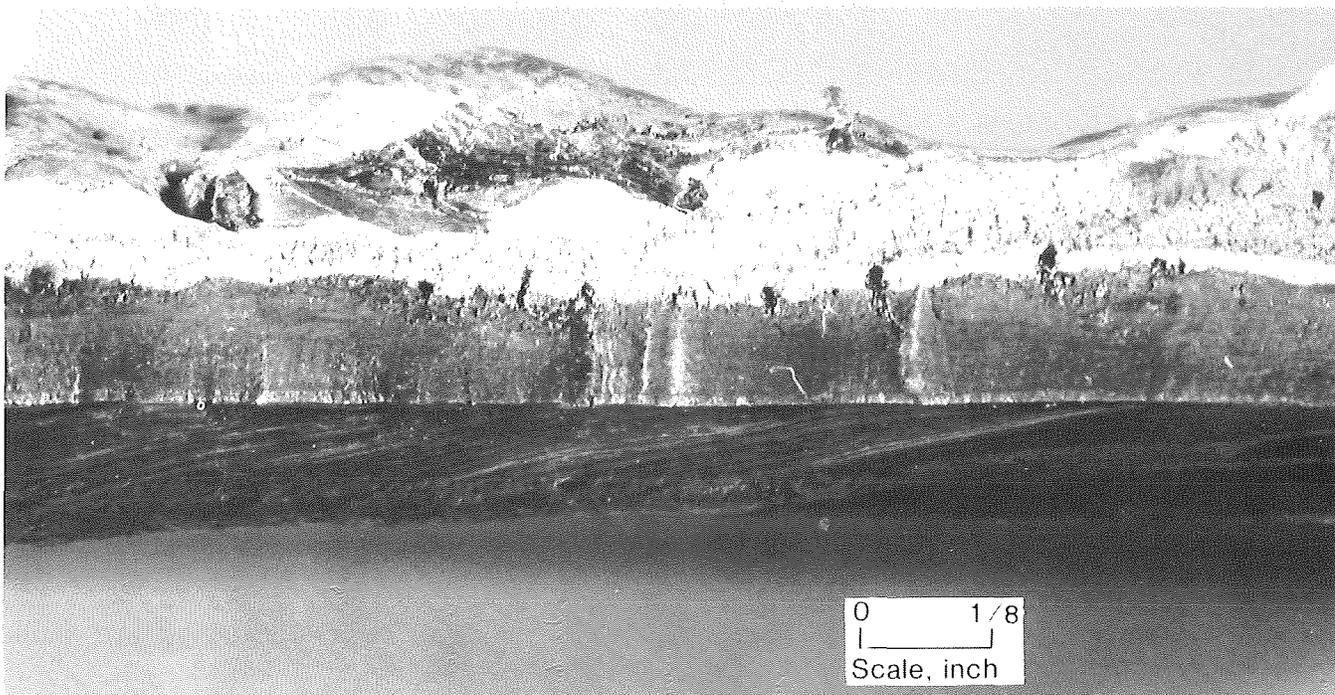


FIGURE 12. - Surface of fatigue crack. The darker portions of the crack contain several ratchet marks or ridges characteristic of high stress and numerous fatigue crack origins.

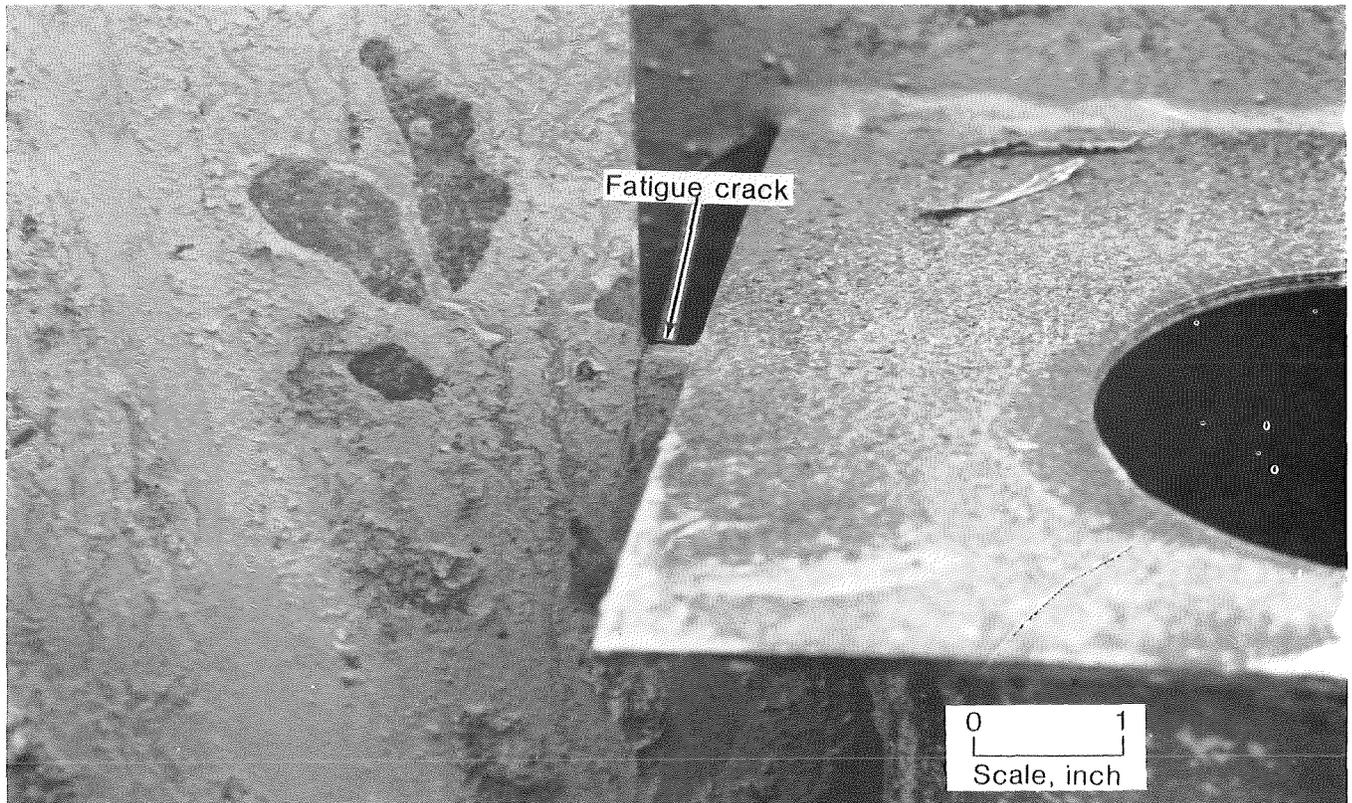


FIGURE 13. - Fatigue crack propagating from a stress concentration.

SUMMARY AND CONCLUSIONS

Verbal and written responses from a total of 29 organizations having experience with building, selling, and/or using diesel exhaust-gas water scrubbers were obtained. These organizations consisted of mine maintenance departments and mine equipment manufacturers. The response from the mines represents experience with 207 diesel units equipped with scrubbers. Mine water and exhaust water scrubber solutions were chemically analyzed and three different stainless steel scrubbers and an exhaust tube from a fourth scrubber underwent failure analysis. The most commonly identified problems consisted of sludge and mineral deposits. This indicates lack of maintenance and/or poor designs where deposits cannot be thoroughly flushed. Weld cracking and metal cracking near mounting areas were found to result from vibration and fatigue. General and pitting corrosion was observed on internal scrubber surfaces. Corrosion of the water level controls was evident in the water-make-up

type scrubbers. Reported service life ranged from 3 months to 10 years and no particular brand was observed to fail at an earlier time than others. Further, there were no problems identified to be characteristic of a specific brand of scrubber. Similar rates and types of failure were found throughout. Seven of eight mine respondents used detergents, soaps, soda ash, etc., when flushing during maintenance. Frequency of flushing ranged from once per shift to once per week. Damage from accidents or abuse was also reported.

Less frequent service problems involve fatigue cracking at stress concentrations, for example, corner and intermittent welds, and general and pitting corrosion. Improper design and incorrect welding techniques were found not to sustain the structural integrity of a scrubber in normal operation where rigid mounting transmits vibration, and flexing stresses. These circumstances

can promote premature failure. Severe pitting corrosion of stainless steel was characterized by corrosion at the water line on exhaust tubes entering the water bath and corrosion on internal surfaces adjacent to welds. Mild steel does not possess sufficient corrosion-resistant properties to be used for water scrubbers. Type 304 stainless steel has demonstrated good corrosion resistance in most applications, the exception being when scrubber water contains high concentrations of chlorides in solution. In these situations, mining operations should use water with a reduced chloride content for filler water. Since type 304 stainless steel has low corrosion resistance to pitting when exposed to high temperature and high chloride content solutions, manufacturers may find it necessary to fabricate scrubbers from more corrosion-resistant materials. Stainless steels containing molybdenum (Mo) have greater resistance to pitting corrosion than type 304 stainless steels (8). Type 316 (2 pct Mo) or type 317 (4 pct Mo) would provide better corrosion resistance in this application. It may

even be necessary to use other materials with higher chromium (Cr), nickel (Ni), or Mo content (special low carbon stainless steels with <0.05 pct carbon (C)). The use of these materials may be prohibited by high costs and fabrication difficulties. The value of "sacrificial plugs" (a high electrochemical potential metal such as zinc) was not determined. In theory, corrosion will attack the plug rather than susceptible areas within the scrubber. There is some question as to the effectiveness of sacrificial plugs (that is, since the rate and severity of corrosion depends on the ratio of the anode area to the cathode area, will single plugs provide sufficient protection to the entire scrubber?).

It is concluded that the problems identified upon the analysis of the failed scrubber units can be minimized by preventive maintenance. Failed units can be adequately repaired with proper welding techniques. Where extraordinary conditions exist, such as mine water high in chlorides, materials are available to construct dependable scrubbers.

RECOMMENDATIONS

1. Adherence to rigid flushing and cleaning schedules is critical for the following reasons:

a. Solid particles and sludge are trapped in the scrubber. If allowed to reside these materials will accumulate, and eventually block internal passages. As a result, scrubber effectiveness as an exhaust-gas cooler and a flame arrester will be impaired.

b. Mineral deposits (particularly calcium compounds) form on internal passages, choking off water flow.

c. Mineral and salt deposits can cake on scrubber walls. When water is added, some of these salts dissolve back into solution.

2. Mine maintenance personnel should periodically inspect all accessible

metal surfaces. To insure longer scrubber life, physical damage and corrosion should be located early and correctly repaired.

3. Mine operators should not fill scrubbers with water containing high concentrations of chlorides, since chloride is highly corrosive even to stainless steel. Filler water should be conditioned to neutralize chlorides, or mine operators should specify special materials for exhaust-gas water scrubbers when ordering equipment from manufacturers.

4. Scrubbers should be totally fabricated from materials with no less corrosion resistance than that of type 304 stainless steel. Mild steel does not possess adequate corrosion resistance against typical scrubber solutions.

5. In fabricating scrubbers, materials that will induce galvanic corrosion should be avoided. All metal parts within the scrubber should have equal electrochemical potential, that is, be constructed of stainless steel throughout.

6. Emphasis should be placed on controlling vibration and reducing areas susceptible to fatigue stresses. Design considerations may include the following:

- a. The use of thicker materials.
- b. Increasing the use of stiffeners and gussets.

c. Limiting the use of intermittent welds.

d. Novel design to reduce number of welds.

e. Improved mounting.

f. Protection from external damage.

7. Do not use mild steel welding rods for repairs on stainless steel.

8. Provide filler plugs that minimize the possibility of filling with the wrong fluid (for example, diesel fuel, hydraulic fluid).

REFERENCES

1. Davis, R. F., and M. A. Elliot. The Removal of Aldehydes From Deisel Exhaust Gas. Trans. ASME, August 1948, pp. 745-750.

2. Dayal, R. K. A Study of Various Critical Pitting Potentials for Type 316 Stainless Steel in Sulfuric Acid Containing Chloride Ions. Nat. Assoc. Corrosion, v. 36, No. 8, August 1980, pp. 433-636.

3. International Nickel Co., Inc. Corrosion Resistance of the Austenitic Chromium-Nickel Stainless Steels in Chemical Environments. New York, 1963, pp. 8-15, 306.

4. Kiefer, G. C., and W. G. Renshaw. The Behavior of the Chromium Nickel Stainless Steels in Sulfuric Acid. Corrosion, v. 6, August 1950, pp. 235-244.

5. LaQue, F. L., and H. R. Copson (eds). Corrosion Resistance of Metals and Alloys. Reinhold Publishing Corp., New York, 2d ed., 1963, pp. 18-31, 54-56, 149-150, 321-323, 347, 378-397.

6. Lawson, A., and H. Vergeer. Analysis of Diesel Exhaust Emitted From Water Scrubber and Catalytic Purifiers. Executive Summary of Final Report ORF 77-01 for CANMET, Energy, Mines and Resources, Ottawa, Canada, DSS Contract OSQ 76-00014, 1977, 160 pp.; available for consultation at the Twin Cities Research Center, Minneapolis, Minn.

7. Linnert, G. E. Welding Characteristics of Stainless Steels. Metals Eng. Quart., v. 7, No. 4, November 1967, pp. 1-15.

8. Lyman, T. (ed.). Metals Handbook. American Society for Metals, Metals Park, Ohio, 8th ed., 1972, v. I, pp. 426, 564-574.

9. _____. Metals Handbook. American Society for Metals, Metals Park, Ohio, 8th ed., 1972, v. VI, pp. 245-259, 266-273, 275.

10. _____. Metals Handbook. American Society for Metals, Metals Park, Ohio, 8th ed., 1972, v. VIII, p. 131.

11. Phelps, E. H., and D. C. Vreeland. Corrosion of Austenitic Stainless Steels in Sulfuric Acid. *Corrosion*, v. 13, No. 10, October 1957, pp. 21-26.
12. Pitt, C. H. Analysis of Corrosion Failure of 304 Stainless Tubing in Diesel Exhaust Scrubbers. Univ. Utah, Dept. Metallurgy and Metallurgical Eng., Salt Lake City, Utah, 1980, 3 pp.; available for consultation at the Twin Cities Research Center, Minneapolis, Minn.
13. Rail Engineering International (Suffolk, England). Diesel Exhaust Conditioning for Underground Mines and Potentially Hazardous Environments. *V. A*, No. 5, July/August 1974, pp. 289-290.
14. Society of Automotive Engineers, Inc. (Warrendale, Pa.). Prevention of Corrosion of Metals. SAE Iron and Steel Committee Meeting, 3d printing, SAE Preprint J447a, 1979, pp. 8-9.
15. Torchio, S. Stress Corrosion Cracking of Type AISI 304 Stainless Steel at Room Temperature--Influence of Chloride Content and Acidity. Lab. of Electro-Chemistry and Metallurgy, Univ. Milan, Italy, 1979, pp. 555-561.
16. Uhlig, H. H. (ed.). The Corrosion Handbook. John Wiley & Sons, Inc., New York, 3d ed., 1951, pp. 136, 152-155, 158-181, 569-571, 578-587, 589.
17. U.S. Code of Federal Regulations. Title 30--Mineral Resources; Chapter I--Mine Safety and Health Administration, Department of Labor; Subchapter D--Electrical Equipment, Lamps, Methane Detectors; Tests for Permissibility; Fees; Part 18--Electric Motor-Driven Mine Equipment and Accessories. U.S. Government Printing Office, Washington, D.C., July 1, 1981, pp. 90-125.
18. _____. Title 30--Mineral Resources; Chapter I--Mine Safety and Health Administration, Department of Labor; Subchapter E--Mechanical Equipment for Mines, Tests for Permissibility and Suitability, Fees; Part 36--Mobile Diesel-Powered Transportation Equipment for Gassy Noncoal Mines and Tunnels. U.S. Government Printing Office, Washington, D.C., July 1, 1981, pp. 235-248.
19. _____. Title 30--Mineral Resources; Chapter I--Mine Safety and Health Administration, Department of Labor; Subchapter N--Metal and Nonmetallic Mine Safety and Health; Part 57--Safety and Health Standards--Metal and Nonmetallic Underground Mines. U.S. Government Printing Office, Washington, D.C., July 1, 1981, pp. 369-418.
20. _____. Title 30--Mineral Resources; Chapter I--Mine Safety and Health Administration, Department of Labor; Subchapter N--Metal and Nonmetallic Mine Safety and Health; Part 75--Mandatory Safety Standards--Underground Coal Mines. U.S. Government Printing Office, Washington, D.C., July 1, 1981, pp. 451-567.
21. Wilkinson, E. R. Mechanical and Metallurgical Control of Sulfuric Acid Corrosion in Petroleum Processes. *Corrosion*, v. 3, No. 5, May 1947, pp. 252-262.

